Powder Technology 332 (2018) 351–358

Contents lists available at ScienceDirect

Powder Technology

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

Particle sizing from Fraunhofer diffraction pattern using a digital micro-mirror device and a single photodiode

Heng Xie [a,b], Lijun Xu [a,b], He Niu [a,b], Zhang Cao [a,b,*]

[a] School of Instrument Science and Opto-Electronic Engineering, Beihang University, Beijing 100191, China
[b] Beijing Advanced Innovation Center for Big Data-Based Precision Medicine, Beijing, China

ARTICLE INFO

Article history:
Received 27 August 2017
Received in revised form 29 March 2018
Accepted 1 April 2018
Available online 04 April 2018

Keywords:
Particle sizing
Scattering measurements
Fraunhofer diffraction
Abel transform
Integral inversion

ABSTRACT

In this paper, a particle sizing method using a digital micro-mirror device (DMD) and a single photodiode was proposed. Firstly, the Fraunhofer diffraction pattern was projected onto the DMD. The integral intensity of the pattern along each line array of the DMD, referred to be a projection, was captured by the photodiode line by line at the aid of a focusing lens. Secondly, the inverse Abel transform was implemented to precisely retrieve the diffraction pattern from the projections. Thirdly, the particle size distribution was reconstructed from the diffraction pattern from the integral inversion. In addition, as only one photodiode was employed, distortions caused by the non-uniformity of multiple detectors were avoided. The center of Fraunhofer diffraction pattern could be automatically located by a hierarchical searching method. Experiments were carried out to validate the proposed method on a commercial particles plate and polystyrene latex spheres. The results demonstrated that the proposed method is effective to retrieve the diffraction pattern and particle sizes.

1. Introduction

Particle size is one of the most important physical properties of powdered substances. Its measurement is widely applied in modern industry and plays an indispensable role in the manufacture of many products [1–9]. For particle sizing in different areas, a variety of effective methods have been proposed, such as microscopy, sedimentation, coulter countering, sieving and light scattering. Among all these available methods, the laser scattering is the most widely used one because it is simple, precise, and relatively fast [10]. The scattering can be precisely depicted by the Lorenz-Mie theory, but the theory is very complicated and typically well simplified by the Fraunhofer diffraction [11,12].

When the particle size is significantly larger than the wavelength of the illuminating light, the Fraunhofer diffraction provides a simplified but also good solution [13,14]. The diffraction intensity can be calculated from a known particle size distribution through the Fredholm integral equation of the first kind. When the size profile is unknown, the intensity of the diffraction pattern must be detected to yield an inversed particle distribution. Typically, a laser beam passes through the particles and is scattered. The scattered light at different angles on the focal plane is inversely proportional to the particle size. The angular intensity of the scattered light is then measured by a series of photosensitive detectors. Usually, the detectors are shaped into arcs and concentrically arranged [15]. In many applications, the center of the concentric detectors should be accurately aligned. Also, the non-uniformity is inevitable among detectors and delicate calibrations of these detectors are very time consuming. Instead of the photosensitive detectors, a linear charge-coupled device can be used for its high measurement resolution and flexibility [16]. However, precise alignment and calibration are still required to achieve high accuracy.

In our previous work, single detector was implemented to remove the non-uniformity among different detectors. A digital micro-mirror device (DMD) was used to reflect the intensity at different angles to the detector [17,18]. As a result, a virtual concentric detector array was constructed to capture the diffraction pattern. The number of the equivalent detectors could be adaptively changed and provided a flexible way for the intensity detection. However, the micro mirrors in the DMD are squarely sized and arrayed; this configuration introduced unavoidable errors in the construction of the concentrically shaped detectors. In this paper, the pattern was detected precisely in an alternative way. The diffraction pattern were projected onto the DMD and recorded by the photodiode line by line. Then the integral intensity of the pattern was captured from each array of the mirrors. Inverse Abel transform was implemented to precisely yield the diffraction pattern from the projections. Then the particle size distribution was reconstructed from the

---

* Corresponding author at: School of Instrument Science and Opto-Electronic Engineering, Beihang University, Beijing 100191, China.
E-mail address: zh_cao@buaa.edu.cn. (Z. Cao).

https://doi.org/10.1016/j.powtec.2018.04.007
0032-5910/

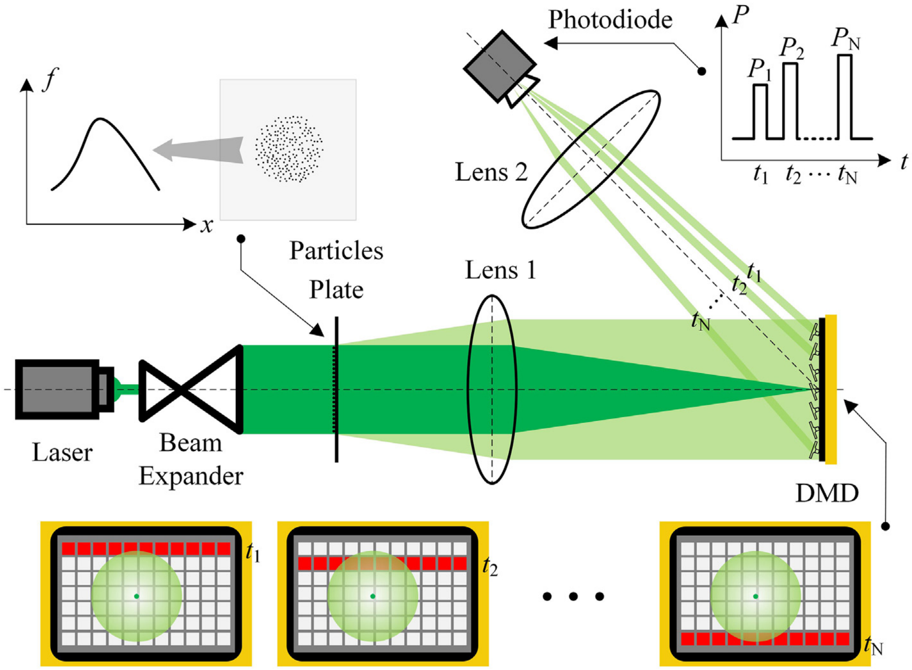


Fig. 1. Schematic diagram of Fraunhofer diffraction particle sizing method.

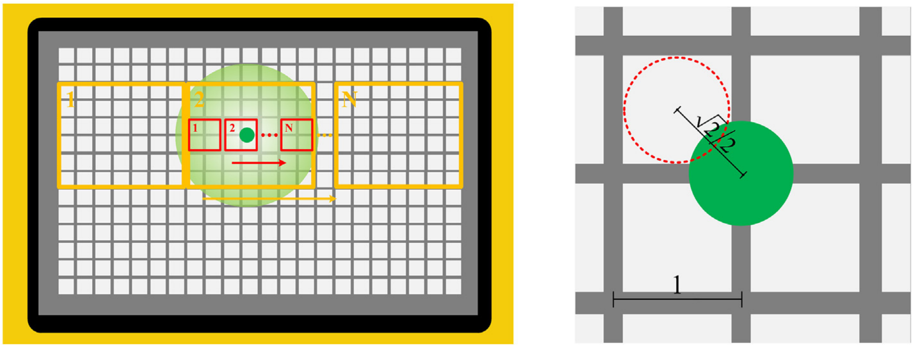
line projections [19,20]. Also, the center of the pattern could be automatically located. Both simulations and experiments were performed to validate the feasibility of the proposed method.

2. Particle sizing via single photodiode

2.1. System overview and automatic alignment

Fig. 1 depicts the schematic diagram of the single photodiode-based particle sizing system. The laser emitted from a light source passes through a beam expander. Then the expanded light illuminates the particles plate with a certain particle size distribution $f(x)$ and generates a diffraction pattern on the focal plane of Lens 1. A digital mirror device (DMD) is placed here instead of the concentric photosensitive detectors or CCD/CMOS array detector used in the traditional way. The DMD is a light switch array with semiconductor-based micro mirrors fabricated by using MEMS technology. One DMD microchip contains more than 7 hundred thousand micro mirrors, each of which is as small as several micrometers. Micro mirrors can be precisely controlled by voltage signals to rotate to two states, switching the incident light into two different directions. In the reflected light path of the DMD, a photodiode is placed behind Lens 2 to collect the integrated light intensity.

As shown in Fig. 1, part of the expanded light is converged to a point at the focal plane of Lens 1. The light intensity of this point reaches the peak value of the intensity, and can be utilized to center the diffraction pattern automatically. The mirrors in the DMD can be switched one by one to go through all the possible intensity and find the center. This ergodic approach can be very time-consuming. A hierarchical searching method was introduced here to reduce the centering time. The DMD is divided into several equal-area parts, as the yellow blocks depicted in Fig. 2 (a). Micro mirrors in the same block are operated as a whole simultaneously, and the reflected light is recorded by the photodiode. The block including the pattern center reflects the strongest light intensity and is selected. The selected block is divided into the smaller red blocks in Fig. 2 (a). The process is repeated till the selected box contains only several micro mirrors. The center can be determined by switching these micro mirrors in turn. Usually, the centering error can be smaller than one mirror in this way. The size of each micro mirror is as small as several micros, and the gap between two neighboring micro mirrors can be neglected. When the center point is located on 2 micro mirrors or more, e.g. as depicted in Fig. 2 (b), the red dotted line shows the



(a) (b)

Fig. 2. Illustration of hierarchical searching method used for center searching. (a) The micro mirrors on DMD are divided hierarchically to search the center point. (b) The maximum error when center point is located on more than 2 micro mirrors.