Holographic imaging of particles

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This work describes the imaging of particles using in-line holography. Single particles are confined in an electrodynamic trap and illuminated by a focused laser beam. A CCD camera is used to record the resulting hologram from which an image of the particle is reconstructed computationally. Examples involving a single glass microsphere and multiple Tunisian sand particles are presented.

INTRODUCTION

The *in situ* characterization of small particles is a persistent objective in applied electromagnetic scattering. Countless examples of measurements and theoretical modeling of the scattering patterns of single and multiple particles can be found in the literature. A typical goal of such work is to infer information relating to the particles' physical form, such as size and shape, by analyzing the angular structure of the scattering patterns. This inference has proved to be very difficult in practice, except for the simplest of cases.

Ideally, one would prefer to image particles directly, thus eliminating the complexity and ambiguity associated with interpretation of the scattering patterns. However, for micrometer sized particles, *in situ* imaging using conventional geometrical optics is not feasible due to the variability of particle position, optical aberrations, diffraction, and the limited numerical aperture of the imaging system. Holography is an alternative that can provide particle images while being free of these limitations. This work will present an apparatus to measure single and multiple-particle holograms and demonstrate the computational reconstruction of particle images from the holograms.

HOLOGRAPHIC IMAGING

In the context of this work, holography is the measurement of the *interference* between the light illuminating a particle and the particle's far-field scattered wave. This interference pattern constitutes a system of fringes measured by the detector, the specific structure of which is controlled by the local relative phase between the illuminating and scattered waves across the detector face. Consequently, the hologram is as complicated as the associated scattering pattern. However, unlike the scattering pattern, a simple computational operation can be performed to render an image of the particle. In short, the hologram is regarded as a transmission diffraction grating and the Fresnel-Kirchhoff (FK) integral is used to calculate its near-field diffraction pattern under plane-wave illumination. This calculation can be done rapidly since the FK integral is evaluated using fast Fourier transforms. The reconstruction

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is done in a plane that is parallel to the hologram; if the plane corresponds to the plane containing the particle during the measurement, the resulting diffraction pattern produces an image of the particle [1]. Otherwise, a blurred image results. The resolution of the image is ultimately limited by the pixel size of the CCD and the wavelength [1]. It is for this reason that computer-based holographic image-reconstruction is a relatively new technology; large CCD arrays with sufficiently small pixels have only recently become economical and widely available.

APPARATUS AND MEASUREMENTS

Fig. 1 shows a picture (a) and the corresponding diagram (b) of the apparatus used to measure single-particle holograms. The design is based on the so-called in-line configuration, where the particle, optical components, and detector are all co-linearly arranged. The light source is a 70 ns pulsed Nd:YAG laser, frequency doubled to 532 nm. This light passes through a Glan-Thompson (GT) polarizer to ensure linear polarization of the light before being focused by lens L_1 onto a 50 µm diameter high-power pinhole. An iris (I) is used to block all but the primary lobe of the pinhole diffraction pattern from reaching a second lens (L_2). This short focal-length lens brings the lobe to a tight waist at a location near the trapping volume of a spherical-void electrodynamic levitator (SVEL). A particle confined in this volume is illuminated by the light diverging from the waist; hence, the waist effectively acts as a virtual point source producing a spherical wave. This wave continues to expand until it reaches the CCD detector along with the scattered light from the particle. The resulting interference pattern between these waves across the CCD constitutes the hologram.

By using a short focal-length lens to form a virtual source near the particle, the light illuminating the particle is more intense than it would be if only the pinhole was used for illumination. This results in a relative amplification of the particle's scattered wave at the CCD face, which enhances the interference structure of the hologram leading to improved particle-image quality. Using a pulsed laser permits the investigation of particle systems in motion. This is especially useful for aerosol applications where particles may be delivered to the apparatus in a flowing stream.

The in-line configuration used to form the hologram is traditionally problematic since the reconstruction process produces both a real and virtual image [1]. These twin images overlap in the reconstruction plane; if one is in focus, the other is blurred and diminishes the quality of the focused image. Using the computational techniques of Xu et al., the influence of the out-of-focus twin image is suppressed in the reconstruction stage [2]. The advantage of the in-line configuration, however, is that it typically requires the least number of optical components. This is important when imaging micrometer-sized particles because ambient dust, which is of similar size and inevitably collects on these surfaces, will contribute to the hologram leading to noise and ambiguity upon reconstruction.

Fig. 2 shows two examples of the particle holograms and their corresponding reconstructed particle-images. One can see in these plots that the technique is successful in imaging particles as small as 20 µm and as large as 300 µm. Modifications to the optical apparatus are planned that are intended to improve the resolution of the imaging process. The ultimate goal of these modifications is to image particle with nominal sizes from one to ten microns,

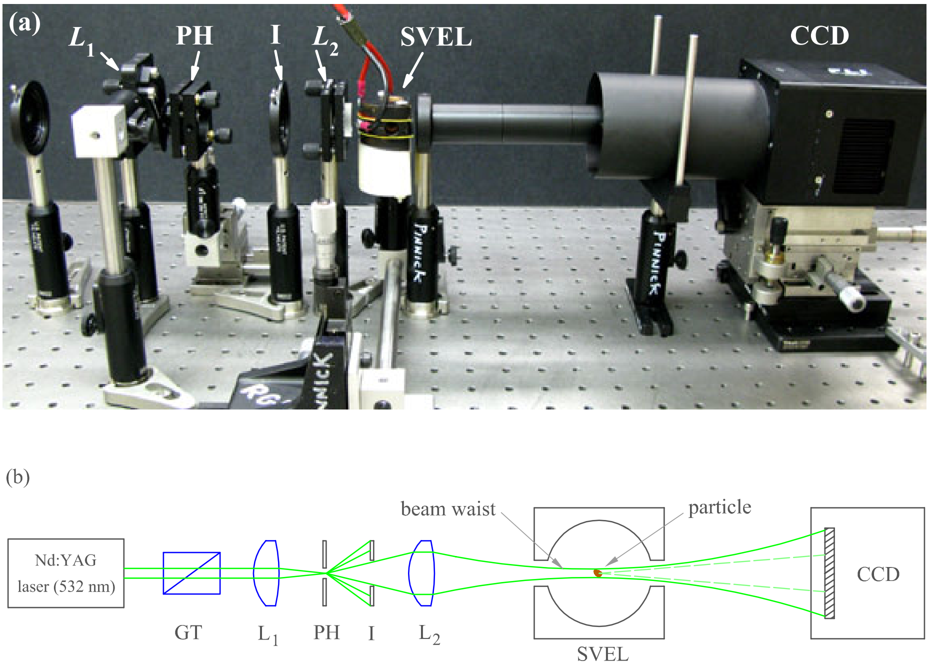

Figure 1. Holographic imaging apparatus (a) and corresponding diagram (b).

which covers much of the size range of environmental aerosols.

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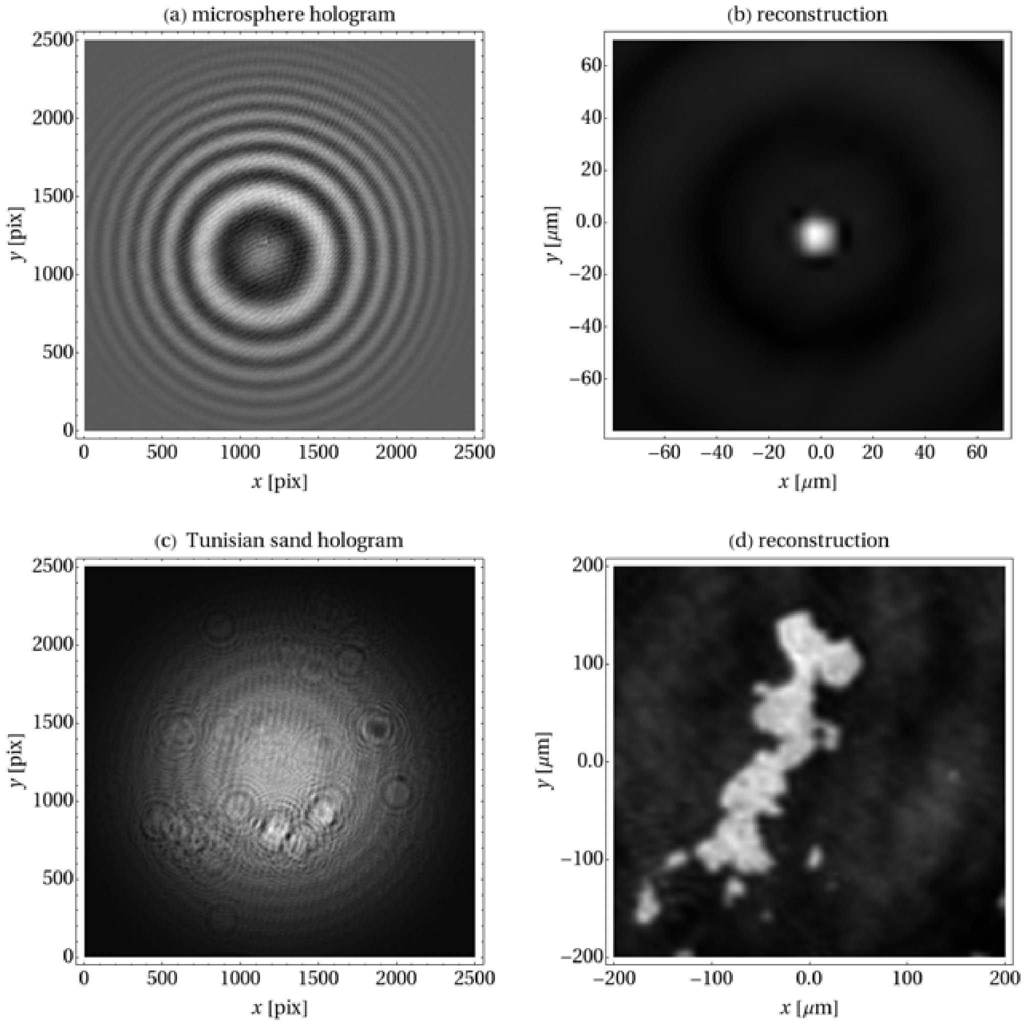

Figure 2. Particle holograms and their reconstructed images. Plot (a) shows the hologram produced by a single 20 μm diameter glass microsphere trapped in the SVEL. The image of this particle reconstructed from the hologram in (a) is shown in (b). The hologram in (c) corresponds to a sample of Tunisian sand particles sprinkled onto a glass slide and placed at the location of the SVEL in Fig. 1. This is done because the sand is too large to be suspended in the SVEL. The reconstructed images of these particles is shown in (d), where one can clearly see the clustered, nonspherical nature of the particles.