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Measurements of size and absorption coefficient of a single moving particle by using dual burst Doppler signal

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ABSTRACT

Modified LDV method is proposed for measuring the diameter and absorption coefficient of a single moving particle by applying the Lambert–Beer's law to dual burst Doppler signal. The diameter and absorption coefficient of a particle are determined simultaneously from the time difference and intensity ratio between burst components of reflected and refracted rays in a dual burst Doppler signal, using only a single photodetector. This method can be applied to a particle larger than the cross-sectional area of an illuminating beam. The optimum conditions of an optical system were estimated theoretically. Experiments were performed with polystyrene particles in water, water droplets, and water-black ink droplets to confirm usefulness of the proposed method.

1. Introduction

The size and velocity of an individual droplet included in sprays that are used for painting, cosmetics, pharmacy and so on, are important parameters for optimizing the size and shape of a spray nozzle. The absorption coefficient of a particle is also useful to characterize their various chromatic properties. So, it is a meaning task to establish a method for simultaneous measurements of velocity, size and absorption coefficient of a single particle in motion. The concentration of a particle in air or liquid can be measured from an intensity ratio of illuminating light and transmitted light under the known absorption coefficient of a particle, which is based on Lambert–Beer's law. In other words, this technique allows us to obtain the absorption coefficient under the known concentration, however, it cannot directly be applied to a single particle in motion. In addition, the size of a particle must be known in advance. The method for measuring the size and absorption coefficient of moving particles has been reported by Onofri et al. [1] by applying the Lambert–Beer's law to Doppler beat signals that can be detected under the principle of the phase Doppler method (PDM) [2–7] which is an extension of the laser Doppler velocimetry (LDV). After that, method for measuring the absorption coefficient simultaneously with the size and refractive index of moving particles has been proposed by Yokoi and Aizu [8], which is based on the polarized-type phase Doppler method (PPDM) [9,10]. In their study, the diameter and absorption coefficient of a moving particle are determined from a pair of signals that are detected by the same photodetector pair, thus, it is not free to adjust the optical condition such as the scattering angle, according to the size and material of the particle to be measured. This problem can be avoided by performing particle size measurements with use of another PDM system of independence. In this case, however, phase deviation of Doppler beat signal caused by interference between reflected and refracted rays on a photodetector cannot be avoided [11–16]. Additionally, this method requires two or more photodetectors in different detection angles, so it is not easy to adjust an optical system. To avoid the above problems, the use of dual burst Doppler signal for particle analysis has been proposed by Nobach [17], which is free from the

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phase deviation and the difficulty in adjustment of the optical system. In that study, however, the measurement of the absorption coefficient of a moving particle has not been discussed.

In this paper we discuss a modified LDV method that detects the time difference between burst components corresponding to reflected and refracted rays and their maximum intensities in a single dual burst Doppler signal to determine the diameter and absorption coefficient of a single particle at the same time, by using only a single photodetector. This method can be used to measure a relatively large particle whose diameter is sufficiently larger than the cross-sectional area of an illuminating beam. We first present a measuring principle of the absorption coefficient that applies the Lambert–Beer's law to the intensities of reflected and refracted rays from a particle and, then, describe the mechanism of temporal separation between burst components corresponding to reflected and refracted rays in a Doppler signal in relation to the scattering angle on the basis of geometrical optics approximation [18,19]. Based on the above discussion, we describe the principle of modified LDV technique that can detect the dual burst Doppler signal containing information on intensities of both reflected and refracted rays. We also numerically estimate the effects of polarization angle of illuminating beam and the scattering angle on measurements to give their optimum conditions in experiments. Finally, experiments are conducted for standard polystyrene particles, water droplets, and ink droplets having various concentrations in volume percentage to show the usefulness of the present method for measuring the velocity, diameter, and absorption coefficient of a single moving particle at the same time.

2. Measurements of particle size and absorption coefficient based on dual burst Doppler signal

2.1. Separation of reflected and refracted rays

Fig. 1 shows a geometrical model of light scattering from a single spherical absorbing particle having an absorption coefficient K under illumination of a single Gaussian laser beam at its beam waist. Here, we consider that a particle diameter d_p is comparable with a beam waist diameter $2w_0$. We also consider a forward scattering scheme in which the efficiency of a refraction process $\alpha_1^{(p)}$ is generally larger than that of a reflection process $\alpha_0^{(p)}$, thus $\alpha_1^{(p)} > \alpha_0^{(p)}$, where $\alpha_1^{(p)}$ and $\alpha_0^{(p)}$ are given with the Fresnel refraction and reflection coefficients, respectively, for perpendicular ($p = 1$) and parallel ($p = 2$) polarizations [16]. Under the forward scattering scheme, the reflected and refracted rays are mainly detected by a photodetector PD on x–z plane, which is placed at a scattering angle ψ from z axis. The second and higher order of refracted rays can be neglected because of their weak intensities in comparison with those of reflected and refracted rays [18].

The intensity of a reflected ray is independent on K, whereas the intensity of a refracted ray is attenuated as K and an optical path length l inside the particle becomes large, which is followed by the Lambert–Beer's law. The intensities I_0^K and I_1^K of reflected and refracted rays from the absorbing particle, respectively, are described as

$$I_0^K = I_0, \tag{1}$$

$$I_1^K = I_1 \cdot \exp(-Kl), \tag{2}$$

where I_0 and I_1 are intensities of reflected and refracted rays for non-absorbing particle having the same diameter as the absorbing one and described as [16,19]

$$I_N = \frac{E_0^2 d_p^2}{4r^2} \cdot \exp\left\{-2\left(\frac{1}{w_0}\right)^2 \left(x + \frac{1}{2} d_p \sin\psi_{Ni}\right)^2\right\} \cdot \alpha_N^{(p)} G_N, \tag{3}$$

where integers $N = 0$ and 1 correspond to the reflected and refracted rays, respectively. E_0 is amplitude of illuminating laser beam at its waist position, r is distance from the particle center to the photodetector, x is the position of particle center on x axis, ψ_{Ni} is the incident angle, and G_N, which is called the gain or the divergence, accounts for the influence that the shape of the scatterer has on the

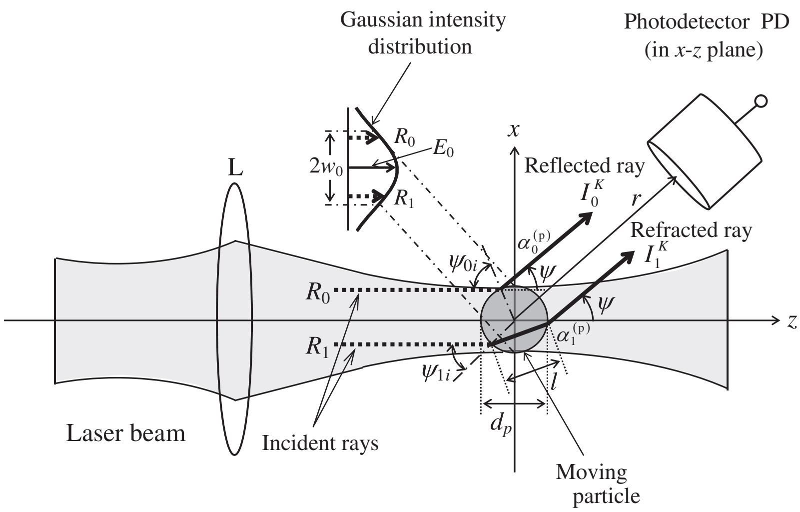

Fig. 1. Basic configuration for measuring the absorption coefficient of a moving particle in the Gaussian laser beam.