New Developments in Phase Doppler Anemometry

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Abstract: This article reviews a number of recent PDA developments designed to either improve accuracy or extend the technique in measurement range or measurand. Many of these developments have depended on improvements in the computation of light scattering from small particles and initially several of these improvements will be discussed. The sensitivity of the dual-mode PDA to particle sphericity will be discussed, followed by possibilities for the sizing of oscillating particles/droplets. Finally, some remarks will be directed to the dual-burst technique and its use in novel optical systems.

Keywords: phase Doppler anemometry, light scattering, particle sizing.

1. Introduction

All optical particle measuring techniques are based on a fundamental understanding of the light scattering, however optimization of a given technique or innovations employing new configurations rely also on being able to conveniently compute and display scattered light fields. One of the first developments to be discussed in this article is therefore a substantial acceleration of light scattering computations achieved through the use of look-up tables and spline interpolations. Also several new forms of graphical representations of the results will be presented.

The second topic to be discussed is the issue of particle non-sphericity and its influence on typical PDA optical systems. It will be shown that the dual-mode arrangement of detectors may provide some interesting opportunities to size certain non-spherical particles or even oscillating droplets. Finally, the dual-burst technique will be revisited, with some emphasis placed on the information contained in the measurement volume shift.

2. Light Scattering Computations

Light scattering computations using the Lorenz-Mie Theory (LMT) (van de Hulst, 1981) or the Generalized Lorenz-Mie Theory (GLMT) (Gouesbet et al., 1988) have typically been rather time consuming and more or less impractical to perform for more complex systems, especially if entire particle trajectories must be reconstructed, as is the case for instance when studying the performance of the dual-burst technique. Therefore efforts to accelerate these computations are welcome or even mandatory for the layout of novel systems.

The Fourier Lorenz-Mie Theory (FLMT) (Albrecht et al., 1995) certainly has the potential for massive parallelization with a speed-up factor exactly equal to the number of processors, although to date this has not been fully implemented. A second avenue for speed-up lies in the pre-computation of all $S_1$, $S_2$ scattering functions and their storage in a look-up table. More specifically, the scattered field is given as

$$E_s = \frac{1}{ikr} \begin{bmatrix} S_1(t_0) & 0 \\ 0 & S_2(t) \end{bmatrix} \begin{bmatrix} -\sin \varphi & \cos \varphi \\ \cos \varphi & \sin \varphi \end{bmatrix} \cdot E_i$$
with

\[ S_1 = \sum_{n=1}^{\infty} a_n \pi_n(\nu) + b_n \tau_n(\nu) \quad S_2 = \sum_{n=1}^{\infty} a_n \pi_n(\nu) + b_n \tau_n(\nu) \]

where \( \nu \) is the scattering angle, \( \phi \) is the second polar angle and \( \pi_n \) and \( \tau_n \) are the corresponding Legendre polynomials. The values of the functions \( S_1 \) and \( S_2 \) can be stored for a selection of particle sizes and refractive indexes, in each case over a range of scattering angles. The main issue to address is the required angular resolution to be chosen in order to insure a given accuracy in the result. By using spline interpolations the number of angular points at which \( S_1 \) and \( S_2 \) are computed and stored can be reduced, however still the required density of points turns out to be dependent on the scattered field itself. For example, a 1 \( \mu \)m particle requires a resolution of approximately \( \approx 1^\circ \), whereas a 100 \( \mu \)m water droplet requires angular steps of between 0.01\(^\circ\) and 0.1\(^\circ\). Therefore, when generating the look-up table, systematic checks are necessary to decide on whether more points are necessary in the spline interpolation or not. The storage space required for the look-up table varies linearly with particle size. One example of such stored data, together with the fitted spline is shown in Fig. 1. This corresponds to the scattered light field from a 100 \( \mu \)m water droplet in the vicinity of the rainbow. The Mie parameter is \( \alpha = \pi d/\lambda = 643.77 \).

A further compression of the data is achieved by using fixed step widths in refining the angular resolution. A data bank has been generated consisting of particle sizes ranging from 1 \( \mu \)m to 838 \( \mu \)m in 1 \( \mu \)m steps and 18 different refractive indexes, which fits onto one 650 MB CD. A second program is then used to define a particular measurement system and to access the stored scattering functions according to the defined apertures, etc. The overall speed-up is presently a factor of 30, with an expected improvement of up to 100. With such speed-up

Fig. 1. Portion of the scattering function reconstruction from stored data using splines: \( \alpha=643.77, m=1.334 \), number of stored points (0\(^\circ\)-180\(^\circ\)) 6105, accuracy 10\(^{-4}\).

Fig. 2. Example computation of phase shift in a PDA system shown as a function of scattering angle and elevation angle (\( \alpha=643.77, m=1.334 \)).