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Modeling drag force acting on the individual particles in low Reynolds number flow

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ABSTRACT

We present a simple model for the hydrodynamic drag force acting on the individual *N* particles of aggregates in uniform flow with low Reynolds number. The present model predicts the shielding effect due to hydrodynamic interactions by considering the individual location and flow direction. The shielding effect of two particles was obtained from curve fitting with the exact solution. Furthermore, the shielding effect of *N*-particles was extended using scaling laws and curve fitting equations. The present model is advantageous in that it can predict the drag force without considering the fractal dimension. In addition, the hydrodynamic interaction between particles can be calculated without matrix operations. The presented model was verified by calculating the drag acting on aggregates with the Filippov method. Verification conditions were that the number of particles was less than 200, and the fractal dimension was in the range of 1.3 to 2.6. Validation results showed good agreement with Filippov's exact solution. The maximum error for the total drag force is within 5%. Finally, we not only applied the drag force model to the discrete element method, but also performed a numerical study of gravitational sedimentation problems at fixed depth.

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1. Introduction

Aggregated particle behavior in fluid flow can be applied to many industrial processes in terms of chemical, pharmaceutical, and biological areas and printing systems. Therefore, it is fundamentally important to understand how particles behave in fluids such as sedimentation, coagulation, breakup, and entrainment. To understand these phenomena, a large number of studies have been conducted to calculate the hydrodynamic force of aggregated particles.

The hydrodynamic forces in a collection of *N* spheres in creeping flow have been studied, beginning with Brenner et al. [1], who determined the exact solution of the drag force of two particles using Smoluchowski's method of reflections. This method has only been applied to cases involving a few spheres because of its complexity and poor convergence [1,2]. Jeffrey et al. [3] used a resistance matrix to calculate hydrodynamic interactions. They studied the drag forces acting on two unequal rigid spheres in a low Reynolds number flow. Brady et al. [4,5] introduced Stokesian dynamics (SD) and accelerated Stokesian dynamics (ASD). Many studies of aggregated particles have been performed using Stokesian dynamics [6–10]. A different approach was proposed by Hassonjee et al. [11] who used a superposition of the *N* fundamental solutions of Lamb [12], expanding the velocity in a series of spherical harmonics centered on individual spheres. Filippov [2] used direct origin-to-origin transformation of spherical harmonics to obtain unknown coefficients from the boundary conditions without using numerical integration, which is considered the most accurate method [6]. Other groups have calculated the drag forces with the full Navier–Stokes

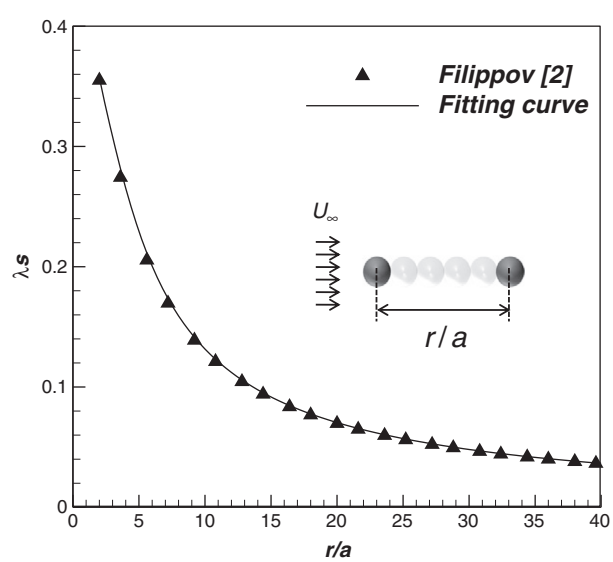

Fig. 1. Shielding effect for two particles with uniform flow parallel to the center line.

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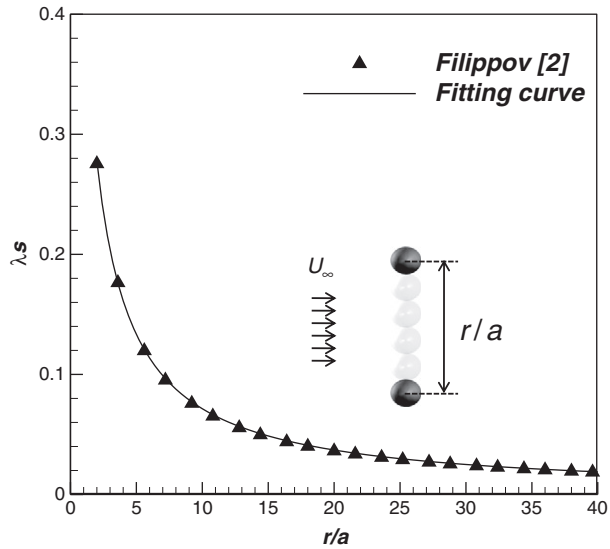

Fig. 2. Shielding effect for two particles with uniform flow perpendicular to the center line.

equations. Hartmann et al. [13] simulated aggregated particles in elongational flow using the finite volume scheme. Peukert et al. [6] analyzed the drag forces of aggregated particles with the lattice Boltzmann method (LBM).

When calculating a large amount of particles, the above methods require a long computational time. Consequently, hydrodynamic force modeling was attempted in order to more rapidly calculate aggregates of the drag force. Aggregated particles have been considered as fractal cluster models. The study of the fractal clusters began with Forrest et al. [14]. Subsequently, hydrodynamic property studies of fractal structures were carried out using the fractal dimension, radius of gyration, hydrodynamic radius, and dynamic shape factors [6,7,15–18]. The cluster models are capable of accurately predicting the drag of aggregated particles. Another approach regards the aggregated particles as porous spheres [19]. A review of the different correlations of the fractal structure and porosity was proposed by Vanni [20]. Higashitani et al. [21, 22] improved Vanni's approach by evaluating the sum of the hydrodynamic drag forces on the individual particles using a correction based on locally defined porosity. Higashitani's model was in good agreement with experimental results of breakup problems by using the discrete element method (DEM) [21].

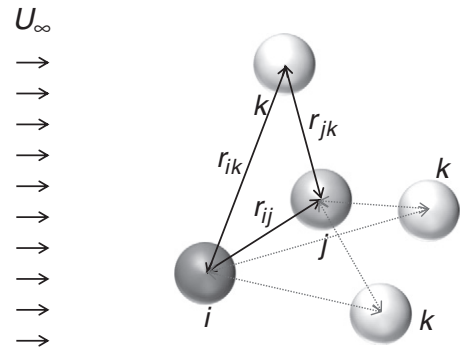

Fig. 4. Schematic for calculating the correlation of the shielding effect.

Many researchers have studied the behavior of fluid-particles using the DEM [23–27]. The DEM is applicable to physical problems by assembling individual particles with a variety of forces. In this paper, we suggest a simple model for hydrodynamic drag forces acting on the individual N particles in creeping flow. The purpose of this model is to easily apply the DEM to a particle settling problem. The model is able to predict the shielding effect due to hydrodynamic interactions by considering the individual location and the flow direction. It uses the shielding effect to predict the drag force without local porosity or matrix calculations. We investigated the drag force on aggregated particles in Section 4.1, and this was verified with the Filippov method. The verification conditions were that the number of particles was less than 200 and the fractal dimension ranged from 1.3 to 2.6. In Section 4.2, we applied the drag force model to the discrete element method and then simulated some cases of gravitational sedimentation problems at fixed depth.

2. Method of multipole expansion

The drag force acting on the particles was calculated using the Filippov method [2]. When N arbitrary particles are in the low Reynolds number flow, the governing equations for creeping flow are expressed as follows:

$$\mu \nabla^2 \vec{V} = \nabla p \tag{1}$$

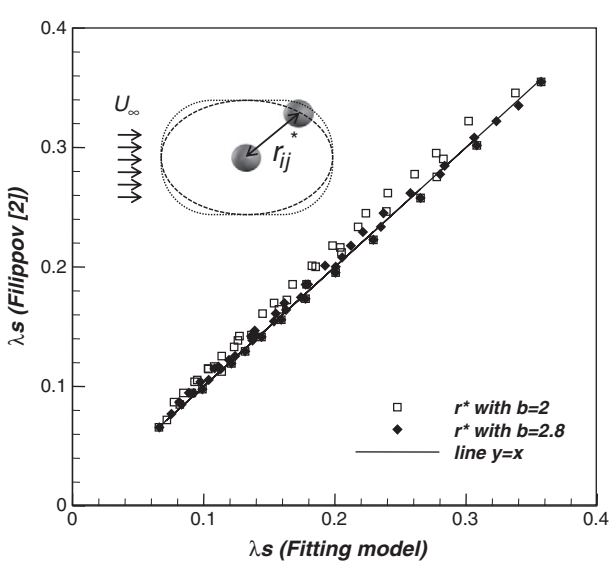

Fig. 3. Shielding effect acting on the arbitrary positions of the two particles.

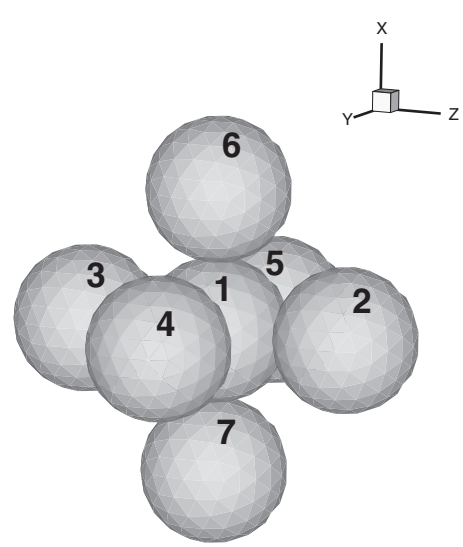

Fig. 5. The 7-particle star in uniform flow. The flow direction was [0,0,1],[0,1,1],[1,1,1].

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