

MOTION OF SPHEROIDAL PARTICLES NEAR WALLS : A MODEL FOR COLLISIONS INCLUDING FRICTION OR ROLLING/GRIPING

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TITLE

Motion of spheroidal particles near walls: a model for collisions including friction or rolling/griping

RESUME

Dans ces travaux, nous développons un nouveau modèle pour la dynamique des particules sphéroïdales dans les écoulements turbulents confinés par des parois. En particulier, le modèle prend en compte l'effet des interactions avec les surfaces sur la vitesse de translation et la vitesse de rotation des particules. Le modèle fait le pont entre les approches par loi de Coulomb, qui prennent en compte un frottement entre deux surfaces en contact, et les approches par coefficient de restitution, qui rendent compte du roulement et de l'adhérence.

ABSTRACT

In this study, we develop a new model for the dynamics of spheroidal particles in turbulent wall-bounded flows. In particular, the model takes into account the effect of interactions between surfaces on the translational velocity and rotational velocity of particles. The model bridges the gap between approaches based on the Coulomb law, which take into account friction between two surfaces in contact, and approaches based on coefficient of restitution, which account for rolling and griping effects.

MOTS-CLÉS : particules en suspension, dynamique de sphéroïdes, collisions sur des surfaces

/ **KEYWORDS**: particle-laden flows, spheroid dynamics, collisions with surfaces

1. CONTEXT & OBJECTIVES

1.1. General context

The dynamics of non-spherical particles suspended in wall-bounded turbulent flows is paramount to several industrial and environmental applications. To name a few examples in the aerosol community, one can cite: (1) the dynamics of blown sand and desert dunes (Bagnold, 2005), (2) the motion of hazardous chemical/radioactive/biological particles near surfaces (Kottapalli, 2023).

1.2. Challenges

The difficulty that arises when studying non-spherical objects near surfaces is that their dynamics is sensitive to their orientation. This leads to complex translational and rotational motion for such anisotropic particles (Voth, 2017). The non-sphericity of particles also impacts how frequently resuspension occurs (Henry 2023, De Souza 2024, Villagran 2024).

To reproduce the orientation of non-spherical objects near surfaces, simulations have to properly account for the interactions between particles and surfaces. The challenge is thus to choose a collision model.

1.3. Objectives

The objective of this work is to develop a collision model that accounts either for Coulomb type friction or for rolling/griping phenomena between surfaces in contact. The goal is to run then fine-scale simulations to explore the orientation dynamics of spheroids in wall-bounded turbulence. Based on these results, we will develop macroscopic models that remain compatible with turbulence models used in large-scale CFD (Computational Fluid Dynamics) simulations.

2. METHODOLOGY

To reach these objectives, we rely on a multi-scale approach : first, fine-scale simulations are performed to extract relevant statistical information and, second, macroscopic models are developed to perform large-scale simulations in realistic cases.

2.1. Fine-scale simulations

Fine-scale simulations are based on a coupling between :

- Direct Numerical Simulations (DNS) of a wall-bounded turbulent flow, which provides information on the instantaneous velocity field ;
- Lagrangian tracking of spheroidal point-particles, each individual particle being described by its position \mathbf{X}_p , translational velocity \mathbf{V}_p , orientation \mathbf{p} and rotational velocity $\mathbf{\Omega}_p$.
- Specific collision models between a spheroid and a surface, either based on a Coulomb law for friction forces or based on a restitution coefficient accounting for rolling/gripping effects (Cross, 2019). These models are used to express the jump on the translational velocity $\Delta\mathbf{V}_p$ and rotational velocity $\Delta\mathbf{\Omega}_p$ as a function of the location of collision and velocities just before collisions (see Figure 1).

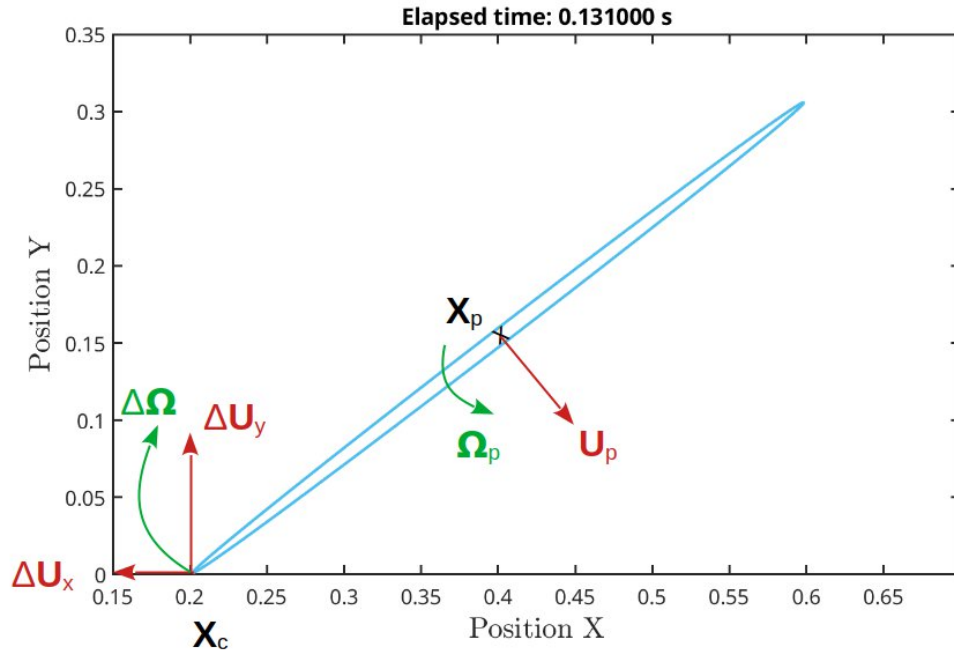


Figure 1. Illustration of the detection and treatment of a collision between a spheroid and a plane.

2.2. Macroscopic simulations

We rely here on stochastic Lagrangian approaches for large-scale simulations, since such models are compatible with RANS formulations (RANS standing for Reynolds-Averaged Navier Stokes), a standard turbulence model used in large-scale CFD simulations. In such models, the fluid velocity is decomposed in terms of its averaged and fluctuating part.

As a starting point, we focus on the case of spheroids without inertia. In that case, the dynamics of spheroids is given by a set of Stochastic Differential Equations (SDEs) that describe the spheroid position \mathbf{X}_p , its translational velocity \mathbf{U}_p and its orientation \mathbf{p} (Campana, 2023). These SDEs include a drift term that explicitly solve the effect of the mean fluid flow on the spheroid dynamics and a diffusive term that models the effect of turbulent fluctuations.

As particles move near boundaries, they can interact with them. In the case of spherical particles, boundary conditions have already been formulated in the literature directly in terms of the particle properties and in the spirit of wall functions, which reproduce the statistical results of the logarithmic region (Minier, 1999). In this study, we propose an extension of these models to the case of spheroids. This implies that we formulate a jump condition on both the translational velocity \mathbf{U}_p and on the spheroid orientation \mathbf{p} :

$$\begin{cases} \mathbf{X}_p(t) = \mathbf{X}_p(0) + \int_0^t \mathbf{U}_p(s) ds \\ \mathbf{U}_p(t) = \mathbf{U}_p(0) + \int_0^t B_v(\mathbf{X}_p(s); \rho(s)) ds + \sigma_v \mathbf{W}'_t + \sum_{0 < s < t} (\mathbf{U}_p(s^-) A_v + C_v) \mathbf{1}_{\text{coll. with } \partial D} \\ \mathbf{p}(t) = \mathbf{p}(0) + \int_0^t B_p(\mathbf{X}_p(s); \rho(s)) ds + \sigma_p \mathbf{W}'_t + \sum_{0 < s < t} (A_p \mathbf{F}(s^-) + C_p) \mathbf{1}_{\text{coll. with } \partial D} \end{cases}$$

where ρ is the density law of $(\mathbf{X}_p, \mathbf{U}_p, \mathbf{p})$ for all $t \in (0, T]$. The second line for the translational velocity includes a drift term B_v , a diffusion term σ_v and jump terms (A_v, C_v) for each collision with the boundary ∂D . The third line for the spheroid orientation contains a drift term B_p , a diffusion term σ_p and jump terms (A_p, C_p) for each collision with the boundary ∂D (which involves \mathbf{F} , an operator that depends on the rotational velocity).

The relation between the jumps functions (A_v, C_v, A_p, C_p) are derived from the statistical analysis of the results obtained with the fine-scale simulations.

3. CONCLUSION

This study explores how the choice of a model for the collision between a particle and a surface affects the dynamics of spheroids near the wall. It serves as a first step towards more advanced stochastic models for the dynamics of spheroidal particles in wall-bounded turbulent flows.

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