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Inertia-Driven Hydrodynamics of Synthetic Active Suspensions in the Low and Moderate Reynolds Number Regime

I Context

Collectives of self-propelled particles exhibit a rich variety of behaviors that are only beginning to be understood. The self-propulsion of isolated particles in fluids is a fundamental problem at the intersection of fluid mechanics and active matter, with relevance to biological locomotion, synthetic microswimmers and particulate transport [1]. In the Stokes limit, propulsion mechanisms are tightly constrained by kinematic reversibility, requiring non-reciprocal deformations or chiral actuation to generate net motion [2–5]. Recent studies have shown that at intermediate Reynolds numbers, fluid inertia fundamentally alters this picture, enabling steady self-propulsion from purely rotational actuation when fore-aft symmetry is broken, as demonstrated for asymmetric spinners, dumbbells and frustum-shaped particles [6–10]. These inertia-enabled mechanisms introduce **new classes of microrobots** and open promising avenues for the design of synthetic active particles operating beyond the Stokes regime [11].

Recently, Chen et al. [10] demonstrated, through combined experiments and simulations, that fore-aft asymmetric particles rotating about their symmetry axis can self-propel in unbounded fluids at intermediate Reynolds numbers. For magnetically driven frustum-shaped particles, axial rotation induces inertia-driven secondary flows and a steep pressure drop along the inclined sidewall, generating a net propulsive force directed toward the narrow end of the particle as depicted in Fig. 1. The associated flow field departs fundamentally from the Stokes-limit rotlet, giving rise to a finite-length vortical structure, termed a *vortlet*. At finite concentrations, these rotating particles exhibit **flocking** behaviour, which remains remarkably well described by a superposition principle. **These results represent a first step into a new realm of synthetic active matter [11]**, yet the underlying hydrodynamic mechanisms remain poorly understood.

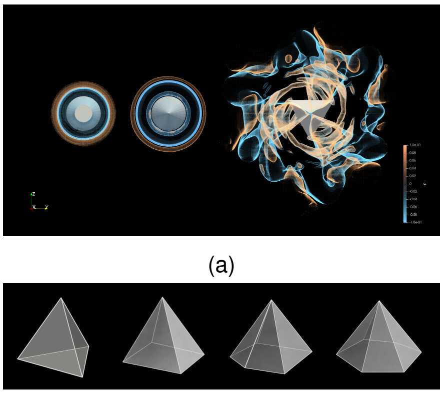
Figure 1: **Spinning, self-propelled particles.** Frustum-shaped spinning particles generate a pocket of pressure drop near the side wall, which pulls the particles toward their narrower end, producing vortlets.

Whether such vortlet-mediated propulsion is specific to frustum-shaped particles or reflects a more general mechanism for rotating fore-aft asymmetric bodies remains an open question. It is revealed that superhelical flow structures generated by rotating flagella play a central role in enabling propulsion at finite Reynolds numbers [12]. The geometric chirality and fore-aft asymmetry of the flagellar waveform produce inertia-driven secondary flows that sustain locomotion beyond the Stokes regime. These results highlight the importance of understanding how particle **geometry and asymmetry** can generate effective thrust through inertial hydrodynamic mechanisms.

II Scientific Objectives

Can vortlets serve as fundamental building blocks for describing collective phenomena in inertial active matter? The objective of this project is to assess the generality of the **vortlet** concept across a broad class of fore–aft asymmetric particle shapes.

- ❒ *Particle scale.* We will elucidate the **hydrodynamic properties** of individual spinners and quantify the role of rotation-induced **vortices** (Fig. 2a) in self-propulsion and particle interactions.
- ❒ *Macroscopic scale.* We will investigate the emergence of **collective dynamics** in assemblies of spinning, self-propelled particles, including the possible appearance of **odd viscosity** and its coupling to coherent motion.



(a) (b)

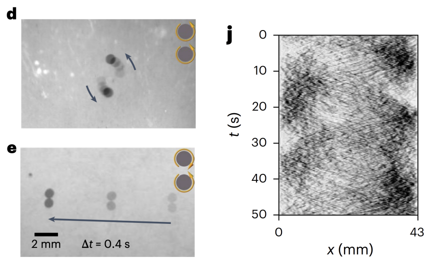
Figure 2: (a) Pressure around a truncated cone, a cone, and a tetrahedron. (b) Representative pyramidal particle shapes.

High-fidelity particle-resolved direct numerical simulations will be performed using adaptive mesh refinement in Basilisk, to accurately capture complex **sharp edges**. The ultimate goal is to establish an effective theoretical framework capable of capturing the essential physics governing self-propulsion and collective behavior in this **new class of inertial active matter**.

III Research Tasks

We consider neutrally buoyant inertial spinners with fore-aft asymmetry under a prescribed torque.

- **Task 1** investigates the influence of particle shape on the propulsion force of a fore-aft asymmetric rotating particle, such as cone, truncated cone, and polygon-based prisms as depicted in Fig. 2b, to establish **propulsion scaling law** and identify the key shape parameters governing **self-propulsion efficiency**.
- **Task 2** studies interaction of two spinning fore-after-asymmetric particles with constant rotation axes as depicted in Fig. 3a, in order to identify the conditions leading to collective motion, **attraction vs. repulsion**. Cargo transport by hybrid **active-passive systems** will also be explored.
- **Task 3** focuses on the **chiral and active flocking behavior** of a dilute suspension in unbounded and cylindrical confined geometries as shown in Fig. 3b. By relaxing the constraint of a fixed rotation axis, an even richer phenomenology is expected to arise, including **spontaneous** symmetry breaking and novel forms of self-organization. Macroscopic rheology behaviors, including the emergence of **odd viscosity** and **nematic ordering**, will be investigated.



(a) (b)

Figure 3: (a) Binary interaction of spinners. (b) 3D chiral active suspension of truncated cones [10].

IV Candidate Profile

We are seeking a candidate with a Master's degree or an engineering degree and the following skills:

- **Fluid Mechanics:** Solid understanding of the fundamental equations (incompressible flows) and the associated physical phenomena. Familiarity with numerical methods and commonly used discretization schemes.
- **Coding & HPC:** Strong proficiency in C/C++ and the Linux environment is essential. Familiarity with high-performance computing (HPC) environments, including script writing, job submission, and performance optimization. Experience with codes such as Basilisk or OpenFOAM would be an asset.
- **Technical English:** Ability to write scientific reports and technical documentation in English.
- **Teamwork:** Ability to work within international teams (potential scientific collaborations with the University of British Columbia and Purdue University) and to communicate effectively.

V Application Materials and Contact Information

Please send your CV and a brief cover letter to Dr. Guodong Gai (guodong.gai@imft.fr), Prof. Olivier Simonin (olivier.simonin@imft.fr) and Dr. Patricia Ern (patricia.ern@imft.fr). We look forward to welcoming you to Toulouse!

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