Annual Report 2023 JMBC – Research Highlight

This highlight refers to the PhD Thesis by Timo van Overveld (2023, Cum laude)

Spherical particles in oscillating flows

From a single particle to pattern dynamics

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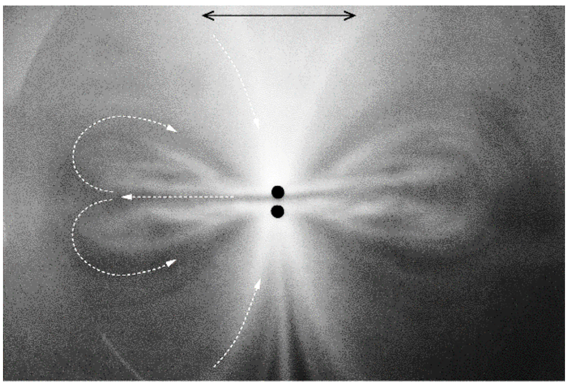
Background

Granular systems are widely present in nature and often exhibit self-organization into patterns. The understanding of these patterns is also essential for many industrial processes, such as the separation of mixtures with multiple granular components. Additionally, a rich range of pattern-forming phenomena can be attributed to the interactions between the grains and the fluid in which they are immersed. Such fluid-immersed patterns are relevant in systems containing colloids, magnetic particles, active matter, or sediment.

One example is the self-organization of spherical particles submerged in a fluid and subjected to horizontal oscillations. When two spherical particles are in each other's vicinity, they align themselves perpendicular to the direction of the flow. This phenomenon is the basis of complex patterns in denser systems, such as one-particle-thick chains oriented perpendicular to the oscillation direction with a regular spacing between them, as shown in Figure 1. The formation of these structures is driven by the nonzero residual flow that remains when averaging over a full oscillation period. This residual flow, known as *steady streaming*, is a nonlinear effect that emerges at intermediate values of the particle Reynolds number, when both viscous and inertial effects govern the system. Our research aims to improve the understanding of the behavior of spherical particles in oscillating flows, from the fundamental dynamics at the particle level to pattern characteristics in many-particle systems.



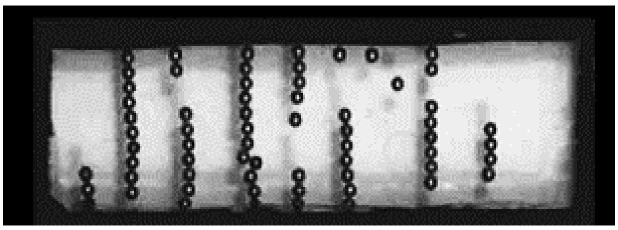


Figure 1. (Left) Two dense spherical particles in an oscillating flow form a stable pair aligned perpendicular to the oscillation direction (Klotsa et al., 2007). (Right) When more particles are present, one-particle-thick chains form, with a regular spacing between them (Klotsa et al., 2009).

Dynamics of a single particle

First, we consider the results of the motion of a single spherical particle in an oscillating flow. The analytical solutions of the Basset-Boussinesq-Oseen equation are derived to describe the particle motion over a smooth wall. The particle motion parallel to the oscillatory forcing is characterized by a single dimensionless quantity: A_r/D, which is the relative particle excursion length with respect to the ambient flow, normalized by the particle diameter. This quantity is directly proportional to the normalized excursion length of the flow, A/D, and further depends on the particle-fluid density ratio $s = \rho_s/\rho_f$ and the viscous length scale normalized by the particle diameter $\delta/D = \sqrt{(2\nu/\omega)}/D$.

Particle pair dynamics

In a next step, we study the dynamics of a pair of spheres in an oscillating box filled with viscous fluid using direct numerical simulations (DNS) of a fully resolved flow, where the particles are modeled using an immersed boundary method (Breugem, 2012) (IBM). Due to the steady streaming flow, the particles align perpendicular to the oscillation direction, moving in elongated *figure-8*-shaped trajectories, with a gap between them, as shown in Figure 2. The pairs and steady streaming flow around them are characterized by two regimes, where either viscous or advective effects dominate. For $A_r/D \leq 1$, the mean particle separation only depends on δ/D, which controls the viscous dissipation of the vorticity within the steady streaming flow. For larger A_r/D values, the mean particle separation increases with A_r/D, which determines the production of vorticity close to the particles and the advection of vorticity away from them. The two regimes are also found in the magnitude of the oscillations of the gap perpendicular to the flow, which increases in the viscous regime and decreases in the advective regime.

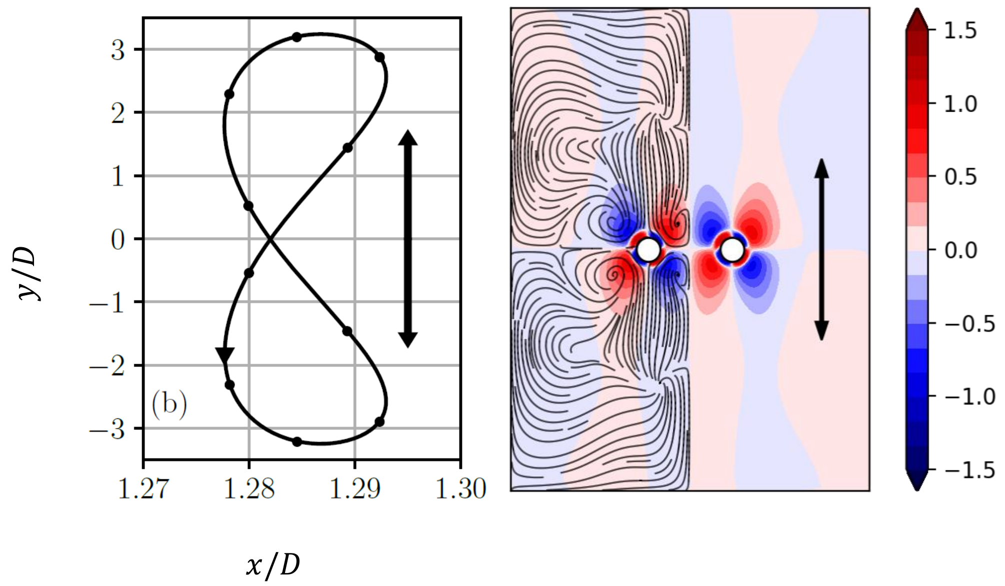


Figure 2. (Left) 'Figure-8-shaped' trajectory of one particle that is part of a stable pair. (Right) The period-averaged out-of-plane vorticity in the horizontal plane through a particle pair, with superimposed streamlines (black curves) and (right), revealing two 'inner' vortices close to each particle and two 'outer' vortices. Vorticity is advected in the oscillation direction in long wakes away from the pair.

Effect of the Stokes boundary layer

Next, the particle pair dynamics in the oscillating box (with bulk fluid and bottom moving in unison) are compared to those in an oscillating channel flow (with bulk fluid moving relative to a stationary bottom). The presence of a Stokes boundary layer above the bottom in the oscillating channel flow leads to fundamental differences in the steady streaming flow, and consequently, in the particle pair dynamics, see Figure 3. The velocity shear within the Stokes boundary layer directly enhances particle rotation through hydrodynamic torque and introduces shear to the spatial structure of the steady streaming flow. Furthermore, the relative motion of the bottom introduces an additional degree of freedom, which controls the particle rotation and the distribution of the period-averaged vorticity over the horizontal plane. The two systems are only equivalent in a limited region of the parameter space. Overall, the particle dynamics in the oscillating channel flow, compared to the oscillating box, are governed by an additional dimensionless parameter, i.e., the particle-fluid density ratio s.

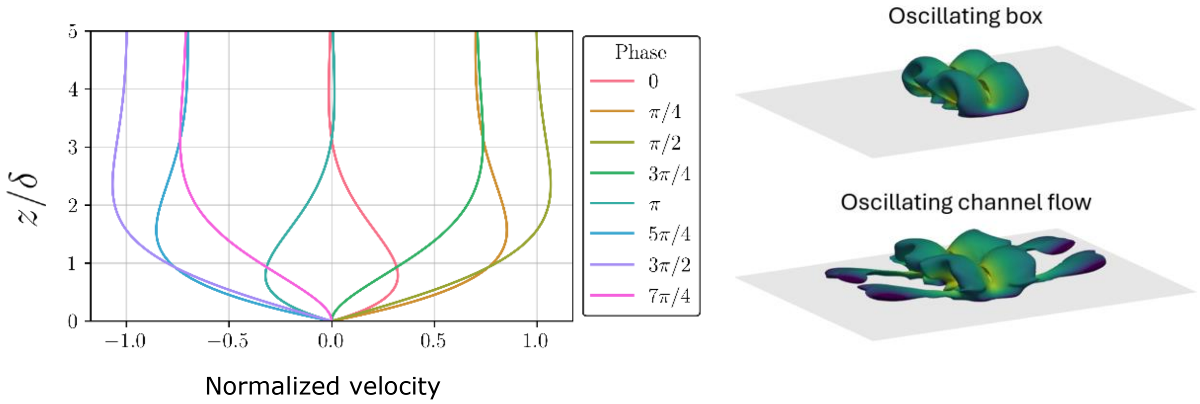


Figure 3. (Left) The Stokes boundary layer profile due to the stationary bottom with respect to the fluid, shown at different times of the oscillation period. (Right) The vortices in the steady streaming flow, visualized using the λ_2-criterion (Jeong & Hussain, 1995), are significantly affected due to the sheared velocity above the bottom in the oscillating channel flow.

Pattern formation in denser systems

The number of particles is substantially increased to study the self-organization into patterns using laboratory experiments in an oscillating box. The interactions between the particles and the steady streaming flow lead to the formation of either one-particle-thick chains or multiple-particle-wide bands, oriented perpendicular to the direction of oscillation, as shown in Figure 4. The normalized spacing between these structures is only a function of A_r/D, implying that it is an intrinsic quantity established by the hydrodynamics. Contrarily, the width of the bands depends on both A_r/D and the confinement, characterized by the particle coverage fraction ϕ. Using the relation for the chain spacing, the transition from one-particle-thick chains to wider bands is given as a function of both A_r/D and ϕ. Complementary numerical simulations show that the regular chain spacing arises from the balance between long-range attractive and short-range repulsive hydrodynamic interactions caused by the vortices in the steady streaming flow, as shown in Figure 5. These vortices induce an additional attractive interaction at very short range when $A_r/D \geq 0.7$, which stabilizes the multiple-particle-wide bands.

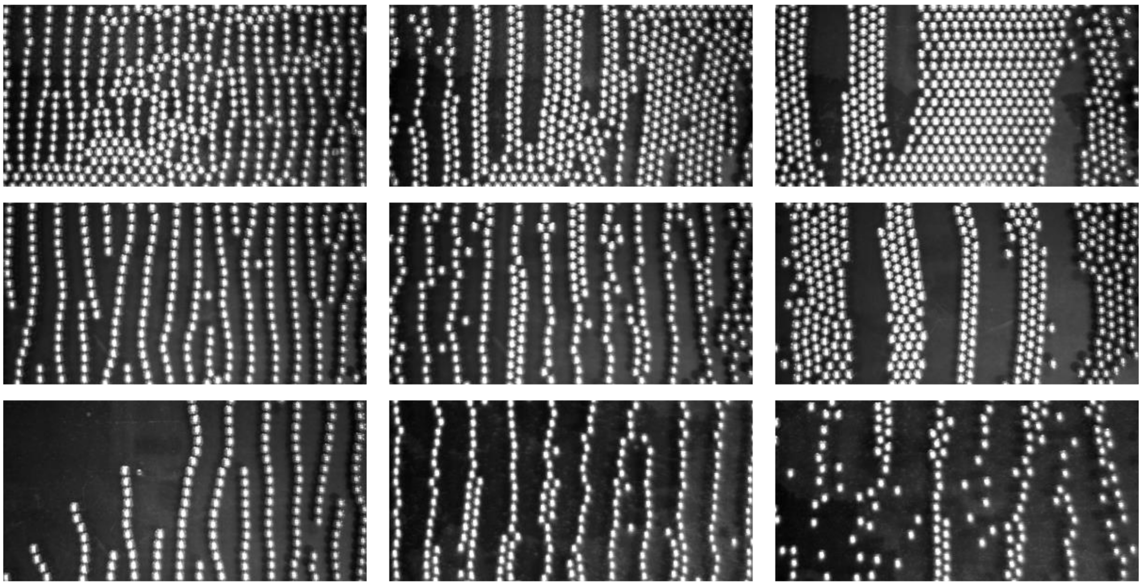


Figure 4. Different patterns are found in the experiments, ranging from one-particle-thick chains to multiple-particle-wide bands, depending on the normalized relative particle-fluid excursion length A_r/D (increasing horizontally) and the particle number density ϕ (increasing vertically).

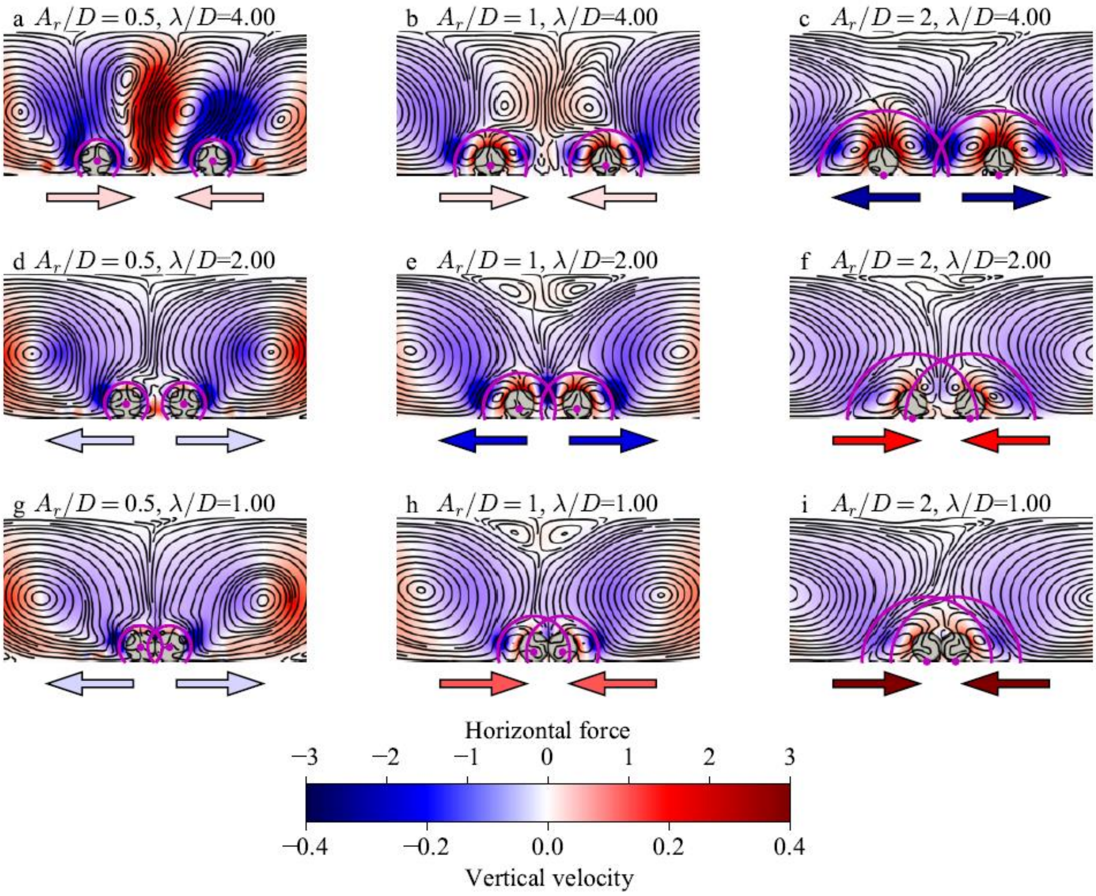


Figure 5. The side-view of the average flow field around two parallel particle chains from our numerical simulations. The chain spacing λ and the relative excursion length A_r are varied. The arrows indicate the direction and magnitude of the horizontal hydrodynamic forces on the particles.

Modeling and control of pattern characteristics

In the remaining parts of the thesis, the pattern characteristics are explored from different perspectives. Using simplified model potentials, the dynamical behavior of the particles due to the complex hydrodynamic interactions is further clarified. The characteristic patterns observed in hydrodynamic experiments are successfully replicated using Monte Carlo simulations. Additional experiments show that the patterns can be controlled through boundary shape effects, e.g., by using serrated sidewalls. These results underscore the potential for pattern control within hydrodynamic systems, not only by changing the hydrodynamic interactions driving the self-organization but also by changing the properties of the confinement.

All in all, our research offers a comprehensive overview of the behavior of spherical particles in oscillating flows, ranging from fundamental dynamics at the particle level to pattern characteristics in dense systems.

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