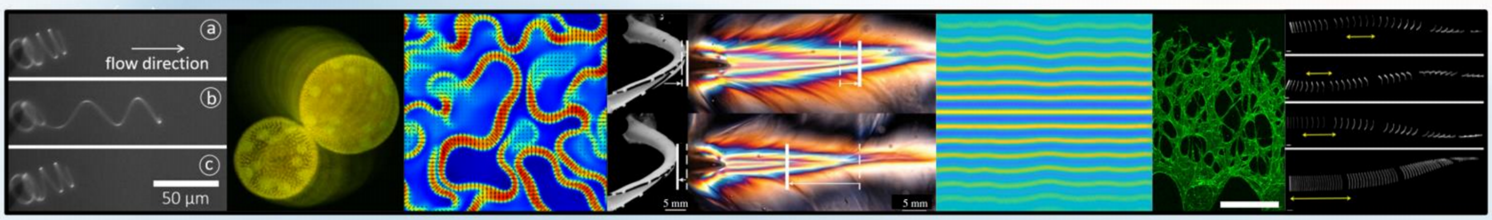
Okinawa Institute of Science and Technology Graduate University

Fluid-structure interactions: From engineering to biomimetic systems

January 14-16, 2020, Okinawa, Japan

Organizers:
Amy Shen & Simon Haward



Mini-symposium

BOOK OF ABSTRACTS

Passive and active particles in Stokes flows

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In the first part of the talk, we consider sedimentation of a rigid helical filament in a viscous fluid under gravity. In the Stokes limit, the drag forces and torques on the filament are approximated within the resistive-force theory. For a wide range of initial conditions, we predict that the center of the helix itself follows a helical path with the symmetry axis of the trajectory being parallel to the direction of gravity. The radius and the pitch of the trajectory scale as nontrivial powers of the number of turns in the original helix. For the initial conditions corresponding to an almost horizontal orientation of the helix, we predict trajectories that are either attracted towards the horizontal orientation, in which case the helix sediments in a straight line along the direction of gravity, or trajectories that form a helical-like path with many temporal frequencies involved. Our results provide insight into the sedimentation of chiral objects and might be used to develop new techniques for their spatial separation.

In the second part of the talk, we discuss our recent results on the transition to collective motion in a suspension of model microorganisms. Combining large-scale Lattice-Boltzmann simulations and a novel kinetic theory we demonstrate that there exist strong correlations between swimming organisms well before the transition. We discuss how these correlations affect the mechanical properties of the suspension and their implication for the nature of the transition.

Biomechanics as a tool for understanding microorganisms

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Despite their tiny size, microorganisms play a huge role in many biological, medical, and engineering phenomena. Because of the considerable influence that microorganisms have on human life, the study of their behavior and function is important. In this talk, we first introduce some of our studies on the behavior of individual swimming microorganisms near surfaces. We show that cells can be trapped at liquid–air or liquid–solid interfaces. We then introduce interactions between a pair of swimming microorganisms, and show that our mathematical models can reproduce the interactions. Collective motions formed by a group of swimming microorganisms are also introduced. We then discuss how cellular-level phenomena can change the rheological and diffusion properties of a suspension. The macroscopic properties of a suspension are strongly affected by mesoscale flow structures, which in turn are strongly affected by the interactions between cells. Hence, a bottom-up strategy, i.e. from a cellular level to a continuum suspension level, represents a natural approach to the study of a suspension of swimming microorganisms. Finally, we discuss whether our understanding of biological functions can be strengthened by the application of biomechanics, and how we can contribute to the future of microbiology.

A three-sphere microswimmer in a structured fluid

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We discuss the locomotion of a three-sphere microswimmer in a viscoelastic structured fluid characterized by typical length and time scales. We derive a general expression to link the average swimming velocity to the sphere mobilities. In this relationship, a viscous contribution exists when the time-reversal symmetry is broken, whereas an elastic contribution is present when the structural symmetry of the microswimmer is broken. As an example of a structured fluid, we consider a polymer gel, which is described by a "two-fluid" model. We demonstrate in detail that the competition between the swimmer size and the polymer mesh size gives rise to the rich dynamics of a three-sphere microswimmer.

Trapping of colloidal particles in flow junctions and porous media via fluid-solute-colloid-boundary interactions

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The flow of colloidal suspensions containing a variety of solutes in flow junctions and porous media is widely found in nature as well as artificial settings such as underground aquifers, hydraulic fractures, water filtration systems, chemical plants, and microfluidics. Such environments often involve merging of multiple streams containing different solutes, leading to spatiotemporal inhomogeneity in the solute distributions. While it is naively expected that the suspended particles advect with the fluid flow, we show that the non-equilibrium interactions between the fluid, solute, colloids, and the boundary enable unique colloidal dynamics that can lead to rapid clogging of the flow junctions. We present a number of scenarios in which the colloidal particles can be captured and accumulate continuously in localized regions in porous media despite the presence of strong pore flow due to the fluid-solute-colloid-boundary interactions.

Near-Wall Dynamics and Assembly of Suspended Colloidal Particles Driven by Shear Flow and Electric Field

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The near-wall dynamics of suspended colloidal particles of radii $a = O(0.1–1\ \mu m)$ flowing through a microchannel are of interest because such particles are usually detected and manipulated by surface-mounted sensors and actuators. Dilute (volume fractions 0.5%) suspensions of fluorescent polystyrene particles were visualized with total internal reflection microscopy within ~1 μm of the wall in combined Poiseuille and electroosmotic flows through ~30 μm deep fused-silica and PDMS-silica channels. The flow is essentially shear flow with a constant shear rate this close to the wall. When the negatively charged particles lag the flow due to electrophoresis, the particles migrate towards the channel centerline; when the particles lead the flow, they migrate towards the negatively charged walls—a behavior qualitatively similar to that observed in inertial migration.

More surprising, in Poiseuille and EO "counterflow," the particles assemble into concentrated streamwise "bands" above a minimum, and in most cases, a minimum after migrating towards the wall. These bands, which exist only within a few μm of the wall, are roughly periodic in the cross-stream direction, although there is no external forcing along this direction. To our knowledge, there is no theoretical explanation for this novel type of directed assembly. Extensive experimental observations, which will be presented in this talk suggest that band assembly consists of three distinct phases: particle accumulation, band formation, and steady-state. This colloidal assembly approach is unique because it is a continuous process that appears to be strongly affected by surface (vs. bulk) particle characteristics.

Inducing motion in flexible solid structures through elastic flow instabilities

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When a flexible object such as an elastic sheet or cylinder is placed in a flow of a Newtonian fluid, the shedding of separated vortices at high Reynolds number can drive the motion of the structure. This phenomenon is known as Vortex-Induced Vibration (VIV) and has been studied extensively for Newtonian fluids. If the same flexible object is placed in non-Newtonian flows, however, the structure's response is still unknown. Unlike Newtonian fluids, the flow of viscoelastic fluids can become unstable at infinitesimal Reynolds numbers due to a purely elastic flow instability. In this talk, I will investigate the fluid structure interaction between a wormlike micelle solution at high Weissenberg number and a flexible elastic sheet and flexible circular cylinder in cross flow. Elastic flow instabilities have been observed for wormlike micelle solutions in a number of flows including flow into a contraction and flow past a circular cylinder. Here we will present a detailed study of the unstable flow past a cylinder for a series of wormlike micelle solutions whose rheology we have fully characterized. Next we will show that a similar elastic flow instability can occur in the vicinity of a thin flexible polymer sheet. We will show that the time varying fluid forces exerted on the flexible sheet can grow large enough to cause a structural motion which can in turn feed back into the flow to modify the flow instability. We will show the same interactions can occur for flexible and flexibly mounted circular cylinders. The static and time varying displacement of the flexible sheets and cylinders, including their oscillation frequency and amplitude, will be presented for varying geometries, for varying fluid flow rates, and for varying fluid compositions and properties. In addition, measurements of flow induced birefringence will be presented in order to quantify the time variation of the flow field and the state of stress in the fluid.

Purely-elastic flow-induced vibrations of cantilevered microcylinders due to a viscoelastic flow instability

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In this talk, I will present a study of the fluid-structure interaction arising from the flow of a shear-banding wormlike micellar (WLM) solution, past both a single flexible microcylinder, and two flexible microcylinders aligned along the channel mid-width at varying separation distances. Using selective laser-induced etching of glass, we have fabricated long cantilevered microcylinders with radii $R \sim 20$ μm and length $L = 1950$ μm. The microcylinders are situated in a microchannel embedded in a single piece of glass. The height of the microchannel is $H = 2000$ μm with its width $W = 400$ μm. Due to the high aspect ratio of the microchannel ($\alpha = H/W = 5$), the flow is approximately uniform along the axial direction of the microcylinder. Using high-speed video microscopy, the tip of the microcylinder is tracked, and its trajectory is analyzed with high spatiotemporal resolution. For the flow of the WLM solution at negligible Re, a purely elastic flow instability occurs above a critical Weissenberg number (Wi), resulting in the fluid flowing preferentially around one side of the post and consequent deflection of the post in both the streamwise and transverse directions. At higher Wi, the flow develops complex spatiotemporal patterns. Similar to the vortex-induced vibrations arising from the inertial instability of viscous flow past a cylinder at high Re, the purely elastic instability of the WLM solution at high Wi results in vibrations of the microcylinder. We present a detailed analysis of these flow-induced vibrations, relate its time-dependence to the properties of the WLM solution and further demonstrate how the fluid-structure interaction couples to a downstream cylinder, resulting in strongly correlated motions that depend on the separation distance between the cylinders.

The asymmetric flow of polymer solutions around cylinders

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Viscoelastic flow around a cylinder is a model problem representing a wide range of relevant industrial processing and biological applications. Reducing the cylinder to microscopic dimensions conveniently enables the problem to be examined in the absence of inertia. Recently, we have developed glass microfluidic geometries containing long and slender, yet rigidly fixed, microfluidic cylinders, which present a low blockage ratio $\beta = 2r/W = 0.1$, where $r = 20$ μm is the cylinder radius and $W = 400$ μm is the channel width. Using a shear-banding viscoelastic wormlike micellar (WLM) solution, we showed how the flow around such a cylinder can destabilize beyond a critical Weissenberg number ($Wi = \lambda U/r$, where λ is a characteristic time of the fluid and U is the average flow velocity), resulting in the asymmetric division of the fluid around either side of the cylinder [Haward et al, Soft Matter **15**:1927]. In the present work we investigate this flow instability in greater detail using a range of polymer solutions formulated from hydrolyzed poly(acrylamide) (HPAA) dissolved over a range of concentration in deionized water. The test fluids present a range of shear-thinning responses under steady shear, and also a wide range of characteristic times. At low HPAA concentrations, the flow around the cylinder remains essentially symmetric for all Wi, but as the concentration increases, so does the maximum degree of the flow asymmetry observed with increasing Wi. Interestingly, at intermediate concentrations, the flow can resymmetrize at very high Wi. We understand these effects by considering simultaneously both the degree of shear-thinning of the fluid and the imposed Wi, and our analysis shows that both strong shear-thinning and high elasticity are required for the formation of strongly asymmetric flows. Our results represent the first report of this highly asymmetric flow state in polymer solutions, showing that it is a general phenomenon and not only specific to WLM. Our analysis provides a clear insight into the origins of this unusual flow state and may also be relevant to understanding other instances of asymmetries arising in shear-thinning viscoelastic flows.

Bacterial swimming instability *via* fluid-structure interactions

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Bacterial cells can swim in a fluid by generating propulsion using their helical filamentous appendages, called flagella, which are connected to the cell surface via a flexible hook. We theoretically and numerically investigate the elastohydrodynamics of swimming bacteria motility. We will discuss the mechanical stability of the swimming and the various cell behaviours emerging from the hook flexibility.

Vascular networks on a chip and their applications

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Due to the capacity of vascular endothelial cells to self-assemble into 3D vascular networks in a conducive hydrogel, it is now possible to grow microvasculature within microfluidic chips that have morphology and function comparable to in vivo capillary beds. These systems have numerous applications including vascularized organs-on-chip, studies of transport across the vascular endothelium, and models of disease. This presentation will focus on the growth of these networks and quantitative analysis of their morphology and transport properties. Results will be discussed showing networks grown from several different sources of endothelial cells that stabilize over 4-7 days, and can then be maintained for periods of over one month. Various accessory cells are used, including fibroblasts, pericytes and mesenchymal stem cells, and these contribute to changes in matrix composition and mechanics over time. Examples will be used to illustrate some of the potential applications of these vascularized models, selected from metastatic cancer, the blood-brain barrier, and cerebral amyloid angiopathy.

Bio-inspired microfluidic pumping by artificial cilia

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Artificial cilia are micro-actuators resembling cilia, actuated to move under the influence of different stimuli such as electrostatic field, magnetic field or even light and pH. These various artificial cilia have been shown to be capable of generating flow and mixing in microfluidic environments. The field of artificial cilia is young, and implementation in commercial products is still remote. The fluid manipulation effectiveness, the ability to locally control flows, and the elegance of potential full integration into microfluidic channels, make them interesting candidates – nature has proven that it works for complex biological applications. In this presentation, we review different methods to manufacture cilia with different actuation properties. In addition, a novel method to realise our youngest generation of magnetic artificial cilia using roll-2-roll printing. In this process, in which a cylinder decorated with micro-pillars rolls over a liquid precursor film that contains magnetic particles, while applying a magnetic field. The spatial arrangement of the cilia can be varied by altering the layout of the micro-pillars on the roll, and the final geometry of the individual cilia can be tuned by varying rheological properties of the precursor material. The high processing speed (up to 1 m/s in our experiments) combined with the large area of production offer the potential to scale up the fabrication of the artificial cilia in a cost-effective and robust fabrication process.

Flow-induced vibrations of a square prism with crossflow-inline freedom

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Flow-induced oscillations of a square prism with crossflow-inline flexibility are examined, and the role of the angle of attack (α) considered. Narrow α bands were observed near α = 0° and 45° (0° having a leading face perpendicular to flow) where the prism responded predominantly with galloping or vortex-induced vibrations (VIV), respectively. At intermittent angles of attack the transition from VIV to galloping was marked by the asymmetric reduction of crossflow-inline displacements for decreasing α as the wake of the prism becomes dominated by single-sided 2S vortex shedding. At 10°, VIV lock-in is lost, and unsteady synchronization creates a beat response in the oscillation orbits. For angles of attack below α = 10°, the prism responds with a galloping-type mode but an additional form of resonance was observed to contribute as well. It was noticed that there is a limited U^* range of 8-12 where inline resonance occurs simultaneously with the galloping response, introducing a third center lobe to the crossflow-inline orbits. Direct force measurements confirmed that odd-integer harmonics in the drag force drive this mode, and flow visualization showed that it coincides with vortex reattachment on the afterbody.

Morphological transitions of flexible filaments in viscous flows

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Here we present the individual dynamics of flexible and Brownian filaments under shear and compression. We use actin filaments as a model system and observe their dynamics in microfluidic flow geometries using fluorescent labeling techniques and microscopic tracking methods. In all cases we combine experimental, numerical and theoretical approaches. Under shear we characterize successive transitions from tumbling to buckling and finally snake turns as a function of an elasto-viscous number. Under compression we reveal the formation of three dimensional helicoidal structures and characterize their formation. Finally, we attempt at linking the microscopic observations to the macroscopic suspension properties with preliminary measurements of the shear viscosity of dilute suspensions of actin filaments in microfluidic rheometers.

Interfacial rheological study on interfacial layer formation of mineral particles with surfactants

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Interfacial behavior of particles in a multicomponent system is necessary to understand to improve or design a new material. Interfacial shear modulus of the oil-water interface with particles was measured under the well-controlled loading of surfactant in order to investigate interfacial localization, adsorption, aggregation, and desorption of particles in the presence of surfactant, especially tested with natural clay and organically modified clay particles. Selectively localized particles responded to surfactants differently depending on interaction between particle and surfactants. Natural clay particles localized at the interface responded rapidly to surfactants as soon as surfactants diffused to the interface and aggregated. Particle aggregates were enhanced to desorb to the sub-phase as the concentration of surfactant increases. Organically modified clays relocalized to the interface with the presence of surfactant first and slowly desorbed to the sub-phase. The incorporated structure of particles with surfactant induce a significant stabilization behavior to the emulsion.

Droplets structured by surface tension gradients on high energy surfaces

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On high energy surfaces, the free energy of the solid/air interface is higher than the sum of free energies of the liquid/air and liquid/solid interfaces. Thus, the canonical behavior for a liquid on a high energy surface is continual spreading, slowed by viscosity. However, evaporation can give rise to solutal or thermal surface tension gradients that cause fluid flow. This flow can change the dynamics and structure of droplets on these surfaces. Here we show cases where droplet spreading is accelerated, reversed, or inhibited as the result of such flows and cases where droplets transition between states over their lifetimes. The mismatch between expected dynamics from energetic arguments with the dynamic structures set by flow imbues these droplets with unique attributes such as negligible contact angle hysteresis and pinning even on geometrically and chemically imperfect substrates. This enables such droplets to move in response to subtle gradients in height, humidity, pressure, temperature, volatile chemicals, and the presence of adjacent droplets and barriers. This work underscores the importance of considering the role of Maragnoni flows in the dynamics and structure of droplets on completely wetting surfaces and enables creation of fluidic machines and potential applications to the cleaning of high energy surfaces.