Workshop Programme

Place: conference center 404 (4F)

Timetable

	28 Oct (Mon)	29 Oct (Tue)	30 Oct (Wed)
09:00-09:30	Registration	Bohr (vortex)	Bohr (plant)
09:30-10:00			
10:00-10:30		Break	Break
10:30-11:00	Opening (from 10:45)	Free discussion/ Excursion	Ishimoto, Y.
11:00-11:30	Takeishi		Chen
11:30-12:00	Seki		Sato
12:00-13:30	Lunch	Lunch	Lunch
13:30-14:00	Tokieda (fluid phenomena)	Free discussion/ Excursion	Tokieda (Modeling)
14:00-14:30			
14:30-15:00	Nakai		Kolomenskiy
15:00-15:30	Break	Break	Break
15:30-16:00	Marcos	Suzuki	Mizuguchi
16:00-16:30	Ishikawa	Liu	Iima
16:30-17:00	Break	Break	Free discussion
17:00-17:30	Ishimoto, K.	Senda	
17:30-18:00	Ohmura	Li	Closing
19:00-21:00		Banquet	

Speakers & Titles

28 Oct (Mon)

- **Naoki Takeishi**（Osaka University）
  "Hemorheology in suspension of red blood cells"
- **Masako Sugihara-Seki** (Kansai University)
  "Lateral migration of particles and blood cells suspended in tube flows"

- **Tadashi Tokieda** (Stanford University)
  “Back-of-the-envelope estimates in fluid phenomena”
- **Tonau Nakai**（Tottori University）
  "Estimation of Chemotaxis Intensity in Bacteria by Using a Mathematical Model"

- **Marcos** (Nanyang Technological University, Singapore)
  “How the bending mechanics of setae modulate hydrodynamic sensing in copepods”
- **Takuji Ishikawa** (Tohoku University)
  “Controlling artificial micro-swimmers by fluid forces”

- **Kenta Ishimoto** (Kyoto University)
  "Elastohydrodynamic stability problems in bacterial swimming"
- **Takuya Ohmura** (Max Planck Institute for Terrestrial Microbiology, Germany)
  "Near-wall dynamics of swimming ciliate"

29 Oct (Tue)

- **<u>Tomas Bohr</u>** (Technical University of Denmark)
  “The shape of flowing water”

- **Kosuke Suzuki** (Shinshu University）
  "Thrust enhancement in the flapping fight of a butterfly model using the immersed boundary-lattice Boltzmann method"
- **Hao Liu** (Chiba University)
  “Passive mechanisms enhance robustness in bio-inspired flight systems”

- **Kei Senda** (Kyoto University)
  "Dynamics and controls of butterflies with experimental observation"
- **Gen Li** (Japan Agency for Marine-Earth Science and Technology)
  "Undulatory fish swimming: sources of drag and optimizations of energetics"

30 Oct (Wed)

- **<u>Tomas Bohr</u>** (Technical University of Denmark)
  “Osmotically driven pipe flows: modeling sugar export from a leaf”

- **Yukitaka Ishimoto** (Akita Prefectural University)
  "A growth model of a plant root system for bridging the transport function of the root and the root environment"
- **Hsuan-Yi Chen** (National Central University, Taiwan)
  "Hydrodynamic model of biological tissues: tissue growth and skin cancer"
- **Katsuhiko Sato** (Hokkaido University)
  "Left-right asymmetric aggregation in Chlamydomonas"

- **<u>Tadashi Tokieda</u>** (Stanford University)
  “Modeling sea, swimming, sound”
- **Dmitry Kolomenskiy** (Japan Agency for Marine-Earth Science and Technology)
  "Scaling laws of the leading-edge vortices"

- **Tsuyoshi Mizuguchi** (Osaka Prefectural University)
  "Kinetic Analysis of Periodic Motion using Accelerometer and Gyroscope"
- **Makoto Iima** (Hiroshima University)
  “Phase reduction of flapping flight and swimming”

28 Oct (Mon)

Hemorheology in suspension of red blood cells

Naoki Takeishi
Department of Mechanical Science & Bioengineering, Graduate School of Engineering Science, Osaka University

I present a numerical analysis of the rheology of a suspension of red blood cells (RBCs) in a wall-bounded shear flow. The flow is assumed as almost inertialess. The suspension of RBCs, modeled as biconcave capsules whose membrane follows the Skalak constitutive law, is simulated for a wide range of viscosity ratios between the cytoplasm and plasma: $\lambda = 0.1$-10, for volume fractions up to $\phi = 0.41$ (Fig.1) and for different capillary numbers (Ca). Our numerical results show that an RBC at low Ca tends to orient to the shear plane and exhibits the so-called rolling motion, a stable mode with higher intrinsic viscosity than the so-called tumbling motion. As Ca increases, the mode shifts from the rolling to the swinging motion. Hydrodynamic interactions (higher volume fraction) also allow RBCs to exhibit both tumbling or swinging motions resulting in a drop of the intrinsic viscosity for dilute and semi-dilute suspensions. Because of this mode change, conventional ways of modeling the relative viscosity as a polynomial function of ϕ cannot be simply applied in suspensions of RBCs at low volume fractions. The relative viscosity for high volume fractions, however, can be well described as a function of an effective volume fraction, defined by the volume of spheres of radius equal to the semi-middle axis of the deformed RBC. We find that the relative viscosity successfully collapses on a single non-linear curve independently of λ except for the case with $Ca \geq 0.4$, where the fit works only in the case of low/moderate volume fraction, and fails in the case of a fully dense suspension. Since this problem requires heavy computational resources, I resort to GPU computing, using the lattice-Boltzmann method for the inner and outer fluid and the finite element method to follow the deformation of the RBC membrane.

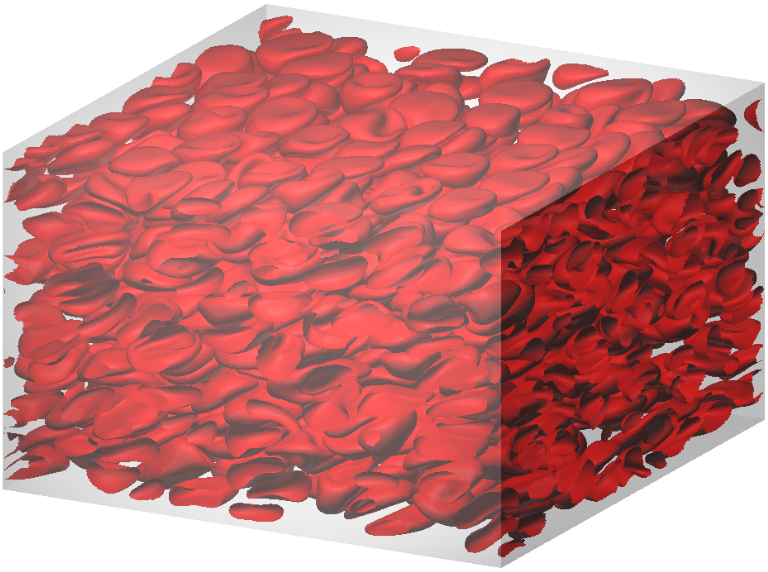

Fig.1 Suspension of RBCs under a shear flow at $\phi = 0.41$.

Lateral migration of particles and blood cells suspended in tube flows

Masako Sugihara-Seki
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Graduate School of Engineering Science, Osaka University

Particles and biological cells suspended in laminar tube flows are known to migrate laterally due to the effects of inertia, deformability, fluid dynamic interactions, and so on. As a result, they are often observed to be focused on specific locations in downstream cross sections of the tube. Recently, lateral migration phenomena of suspended particles/cells flowing through microchannels have gained considerable attention in the field of microfluidics due to their broad range of applications, such as in the separation and filtration of particles and biological cells. In this study, we present various types of focusing patterns of rigid particles or red blood cells over the tube cross section, when their dilute suspensions flow through circular or rectangular tubes several tens to hundreds of micrometers in diameter. Although numerous microfluidic devices with complicated geometries have been proposed, we confine ourselves to straight tubes with a uniform cross section, in order to study fundamental properties of focusing of suspended particles/cells in the flow.

We used dilute suspensions of rigid spherical particles, red blood cells or glutaraldehyde-hardened red blood cells. Rigid particles were suspended in a glycerol-water mixture, the density of which was matched to that of the particles. Red blood cells were suspended in either of phosphate buffered saline (PBS) or dextran solution (PBS containing 1% bovine serum albumin and 10% dextran 40). They were made to flow through a microtube by use of a syringe pump. The locations of suspended particles/cells over the tube cross section were measured by a newly devised observation system, in which 'enface' views of the tube cross section were obtained at a small distance upstream of the tube outlet by a longitudinal observation from the downstream side along the center axis of the tube.

At low Reynolds numbers (*Re*), normal red cells rapidly migrated away from the tube wall so that they were focused near the tube axis in the downstream cross section, whereas rigid particles were dispersed widely over the tube cross section at the same flow condition. For glutaraldehyde-hardened red cells, the axial migration decreased, with increasing concentration of glutaraldehyde. These experimental results indicate the essential role of deformability of red cells in their axial accumulation commonly observed in blood vessels. At elevated *Re*, red cells suspended in dextran solution exhibited lateral migration towards the tube center, whereas red cells suspended in PBS were focused on a ring. Its radius was slightly smaller than that of the so-called Segre-Silberberg annulus observed for rigid spherical particles. Thus, the formation of the focusing ring was attributed to the inertial effect. The axial focusing of red cells in dextran solution might be associated with the viscoelastic property of the dextran solution. Several previous studies reported that rigid particles suspended in viscoelastic fluids migrated towards the tubes axis at comparable *Re*. As *Re* increased, the competing effect of inertia and viscoelasticity induced complicated focusing patterns of suspended particles in the downstream cross section, dependent on *Re*, the particle-to-tube diameter ratio, and the property of the suspending medium.

This research was partially supported by JSPS KAKENHI Grant Number 17H03176 and the ORDIST group fund of Kansai University.

Estimation of Chemotaxis Intensity in Bacteria by Using a Mathematical Model

Tonau Nakai, Taishi Ando, Fumiya Nakamura, Yasutoshi Higashida, Tomonobu Goto
Faculty of Engineering, Tottori University

Bacteria exhibit chemotaxis by repeating a straight swimming (run) and an abrupt change of the swimming direction (tumble). Cells can detect the change in the concentration of a chemical attractant during the run and decrease the frequency of the tumbles if the cells have swum toward the favorable direction. As shown in Fig. 1, a mathematical model has been proposed where the probability of tumbling is correlated with the chemotaxis intensity α [1]. In this study, we observe the chemotactic behaviors of bacterial cells and compare the measurement with the mathematical model to quantify the chemotaxis intensity.

A bacterial strain, *Salmonella typhimurium* SJW1103, was used in the capillary assay, where cells accumulate around the tip of a capillary filled with an attractant (L-serine). Figure 2 shows distribution of the run duration, the time between two successive tumbles. Cells are categorized into two groups depending on their swimming direction in the concentration gradient of an attractant. The run duration is larger for "up the gradient" than "down".

The above observed run duration is compared with the biased random walk model to estimate the chemotaxis intensity α. By using the average run duration for "up" direction (t_u) and "down" (t_d), we obtain$\alpha = 1 - t_d/t_u \approx 0.35$.

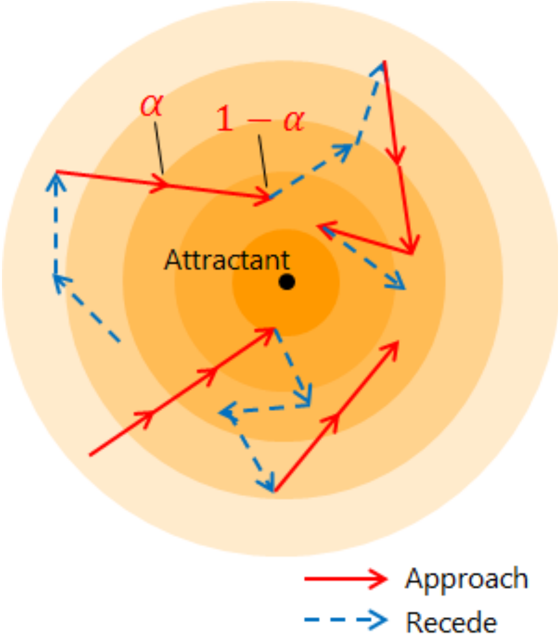

Fig.1 Simulation model based on the biased random walk. Each cell migrates a constant distance Δr in one time step, corresponding to each arrow in the figure. Cells receding from the attractant source always tumble, whereas the behavior of cells approaching is stochastically determined with the probability α.

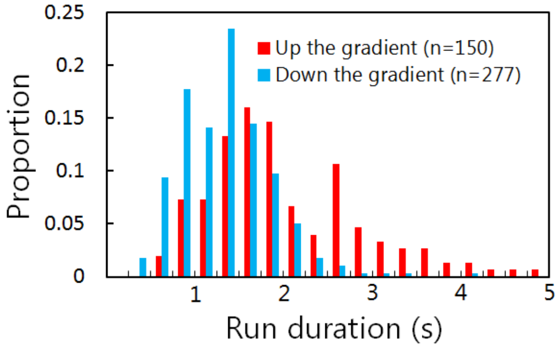

Fig.2 Distribution of run duration (the time between neighboring two tumbles) of the cells under the existence of an attractant (L-serine). Runs were categorized into up and down the gradient depending on the cells' swimming direction in the concentration field.

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How the bending mechanics of setae modulate hydrodynamic sensing in copepods

Marcos
Nanyang Technological University, Singapore

Copepods utilize their mechanoreceptional sensors, known as setae, to sense the hydrodynamic disturbance induced by the swimming planktonic preys, potential mates and predators. The setae are thin and long hair-like structures that protrude from the first antennule and other appendages of the copepods, and bend in response to the flows induced by these sources. While the flows are crucial for the mechanoreception of copepods, there is little knowledge on how the spatial and temporal patterns of these flows cause the deformation of the copepod's mechanoreceptional seta.

In this talk, I would like to address how the setal deformation mechanics regulate the sensing capabilities of copepods in two sensing modes. First, when a copepod stops the beating of all its appendages and “listen” to the flow disturbance due to other sources, the low-Reynolds number flow across the seta is solved by the method of regularized Stokeslets and further related to the setal deformation pattern by the resistive force theory. We demonstrate that the detailed geometry of the first antennule has non-negligible effects on the flow profile across the seta, and find that lower frequency flows lead to larger setal bending and are more easily detected. The response time of setal bending to hydrodynamic signals is studied, and we find short response times consistent with the rapid behavioral and neurological response of copepods.

Second, when a copepod periodically beats its appendages to generate a flow in the anterior-posterior direction, we study these laminar flow by using the immersed boundary method. We also investigate the flow disturbance of other source when subjected to the suction flow causes the setal deformation and may be sensed by the copepod.

Controlling artificial micro-swimmers by fluid forces

Takuji Ishikawa
Dept. Finemechanics, Grad. Sch. Engineering, Tohoku University

Artificial micro-swimmers have attracted strong research interest due to their potential environmental and medical applications. The motility of micro-swimmers enables them to manipulate objects, carry chemicals, and react to their environment; therefore, they can be utilized in therapeutic treatments, sensing, and environmental remediation. To date, a wide variety of propulsion mechanisms have been proposed to generate motility in micro-swimmers. Recently, some studies have attempted to establish an assembly of micro-swimmers to generate stronger forces or large-scale mixing. The stable assembly of multiple micro-swimmers could be a key technology for future micromachine applications. Thus, in this article, we first discuss the stability of a dumbbell micro-swimmer[1]. Our results demonstrated that stable side-by-side swimming can be achieved by pullers. When the aft squirmer was a strong pusher, fore and aft swimming were stable and swimming speed increased significantly. The findings of this study will be useful for the future design of assembled micro-swimmers.

Next, we introduce a novel micro-capsule swimmer that consists of an elastic membrane containing a rigid sphere that is connected to the capsule membrane by springs. Density of the fluid inside the capsule is smaller than that of the surrounding fluid, while density of the rigid sphere is larger than that of the surrounding fluid, though the micro-capsule as a whole is neutrally buoyant. When fluid oscillations are applied, opposing body forces are generated between the internal fluid and sphere due to the density mismatch. The opposing forces induce nonreciprocal body deformation, which leads to migration of the micro-swimmer under Stokes flow conditions[2]. By sequentially imposing three types of fluid oscillations, we successfully controlled the micro-swimmer to draw a Π-shaped trajectory[3]. These results illustrate that the position and trajectory of the micro-swimmer can be controlled arbitrarily in three dimensions.

We also found that the micro-capsule swimmer could migrate vertically downward, even when random forces were applied[4]. We developed a simple mathematical framework to describe the deformation induced migration by noise. The theory could predict the effect of various parameters on the net migration, and the importance of force strength, relaxation time and deformability. The obtained knowledge forms fundamental basis of migration mechanism of a micro-swimmer by noise, and is useful for harnessing energy from low Reynolds number flow.

References

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Elastohydrodynamic stability problems in bacterial swimming

Kenta Ishimoto
Research Institute for Mathematical Sciences, Kyoto University

Bacteria, which form the largest domain of prokaryotic microorganisms, have survived for billions of years with using their sophisticated structures. Many bacteria can swim in fluid and the hydrodynamics of their swimming has been investigated for many decades. Bacterial swimming is achieved by the propulsion of helical appendages, called flagellar filaments, which are attached to the cell body and rotated by the motor at the base of the connection.

Due to the small size of the bacterial cells, the fluid motions around them should obey the Stokes equations of the low-Reynolds-number flow. The time-reversal nature of this fluid equations imposes a mechanical constraint on their locomotion, known as the scallop theorem, which states that reciprocal deformation cannot generate any net locomotion. The bacteria cells can change their swimming directions with reversing the rotation direction of the motor to explore the surrounding environment, and the reorientation is enabled by a short flexible hook that connects the rotary motor to the semi-rigid flagellar filament with being escaping from the mechanical constraints of the scallop theorem.

In this talk, we consider a mathematical model of bacteria swimming with incorporating the flexibility of the hook as a simple torque spring at the connection of the flagellar filament and the cell body. We will then discuss elastohydrodynamic stability problems emerging from the hook flexibility.

We start with establishing a general theoretical framework for bacterial swimming based on the resistive force theory and consider the mechanical stability for the swimmer with symmetrically distributed flagella as a model of a peritrichous bacterial cell such as *Escherichia coli*. We mathematically demonstrate that there can be at most 6 unstable modes which are associated with the degrees of freedom of the rigid motion.

We proceed to the bacterial swimming near a rigid substrate, with focusing on the dynamics of mono-flagellated bacteria such as *Pseudomonas aeruginosa*. It is found from the numerical computation via the boundary element method that the hook elasticity enables the cell to stably stand upright near the boundary like a low-Reynolds-number spinning top. With theoretical analysis based on the resistive force theory, we have revealed that the elastohydrodynamic coupling between the hook flexibility and the rotation of the cell body contributes to the stabilisation of the upright configuration.

Our theoretical and numerical results of the swimming stability are compatible with experimental observations and, interestingly, the stability results are dramatically different, depending on the rotating direction of the flagellar motor. These suggest significance of the hook flexibility in the bacterial locomotive strategies and also highlight the sophisticated structures in nature.

Near-wall Dynamics of Swimming Ciliate

***Takuya Ohmura[1], Yukinori Nishigami[2], Masatoshi Ichikawa[3]**
[1]Max Planck Institute for Terrestrial Microbiology, [2]RIES, Hokkaido University,
[3]Graduate School of Science, Kyoto University

One kind of microorganisms, ciliate, has hair-like organelles called cilia around a cellular body, and plays a crucial role in aquatic ecosystems. In water environments, swimming ciliates are known to accumulate near solid boundaries (e.g. other cells, a bottom of pond, surfaces of stones and waterweed). Why do they accumulate near surfaces? The reason is to make situation easy to get nutrient on the surfaces efficiently. Then, how do ciliates achieve the accumulation? In this study, we would like to find out the mechanism of ciliates' behaviors near a wall from physics approaches.

One hydrodynamic model for microswimmers, called "Squirmer model" [1], can categorize swimming cells into three types, pusher, puller and neutral swimmers. Pusher and puller swimmers are for swimming cells with flagella (e.g. mammalian sperm cells, *Escherichia coli*, *Chlamydomonas*), and neutral swimmer is mainly for ciliates (e.g. *Paramecium*). Near-wall dynamics of pusher and puller swimmers has been studied by experiment and hydrodynamic theory [2, 3]. In contrast, there were less knowledge about behavior of ciliates near a wall. Then, we compared an actual ciliate with hydrodynamic model by experiment and numerical calculation.

In our observation, ciliates, *Tetrahymena pyriformis* and *Paramecium caudatum*, slid adjacent to a wall after colliding the wall (FIG. 1). However, a normal neutral swimmer in Squirmer model swims away from a wall. Then, we developed the numerical model with boundary element method (BEM) from more precise microscopic observations (FIG. 2). As a result, the developed model reproduced the experimental sliding motion. In conclusion, we identified the near-wall dynamics of ciliates could be determined simply by two physical parameters [4, 5].

FIG. 1 The ciliate cell (*T. pyriformis*) sliding on a glass wall. The direct image (top) and the reflected virtual image (bottom).

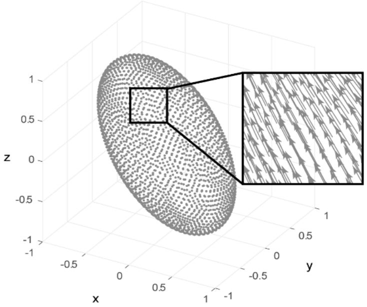

FIG. 2 Mesh and drag force with BEM in the numerical model.

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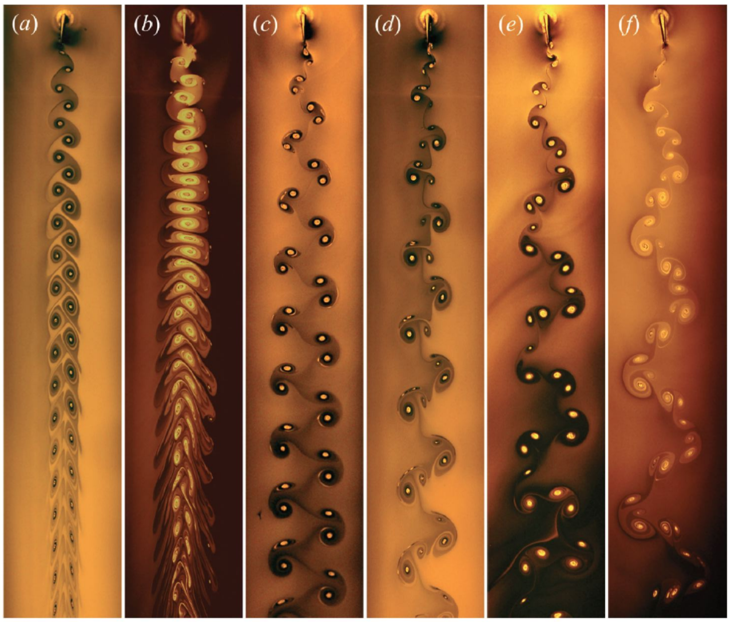
29 Oct (Tue)

The shape of flowing water

Tomas Bohr
Physics Department, the Technical University of Denmark

When we observe fluid flows in nature, it is often because we notice the deformation of the fluid surface e.g., when light reflects on a water drop or an ocean wave. Such deformations can have great beauty and complexity, since the shape of the free surface is intimately and very nonlinearly coupled to the internal flow. In the talk, I will show examples of surfaces with shapes of thin needles or sharp walls and that lead to interesting symmetry breaking transitions, where sharp corners and polygonal structures appear - even in strongly turbulent flows. The existence of such structures, even in very “simple” flows, shows the complexity of the solutions to the Navier-Stokes equations with a free surface. The basic phenomena determining these structures are *separation* and *vortices*. This is shown very clearly in the wakes behind oscillating bodies like fish fins or insect wings, which can be reproduced in a flowing soap film. Since the work of Madelung in the 20’ies, it has been known that the Schrödinger equation can also be expressed as a kind of fluid flow, and it has been suggested by Y. Couder and his collaborators that the mysteries of quantum mechanics can be imitated by bouncing droplets interacting through surface waves. I shall discuss this exciting possibility briefly, but also why the full spectrum of quantum effects cannot be obtained in this way.



Wakes behind an oscillating flipper in a soap film

Thrust enhancement in the flapping fight of a butterfly model using the immersed boundary-lattice Boltzmann method

Kosuke Suzuki, Fumiya Nakai, and Masato Yoshino
Institute of Engineering, Academic Assembly, Shinshu University

Butterflies have unique and interesting features compared with other insects. The most conspicuous example is their erratic trajectory and large variation in speed. This behavior suggests that butterflies have outstanding agility and maneuverability, which are attractive features in practical applications such as micro air vehicles (MAVs). In order to incorporate the outstanding features into artificial aircrafts, we have to know how butterflies enhance aerodynamic forces, save power expenditure, and control their attitude while flying.

We have been studying the flapping flight of a simple butterfly model composed of two thin rigid wings and a rod-shaped body [1]. This model flaps its wings downward to generate lift force and backward to generate thrust force like an actual butterfly. In our previous study, it was found that this model can generate enough lift force to support an actual butterfly's weight even in its free flight from the resting state. However, the thrust force generated by this model was so small that the forward-speed was much smaller than the cruising speed of an actual butterfly.

In the present study, we attempted to enhance the thrust force of the butterfly model by changing the center of the flapping angle θ_c and the lead-lag angle γ. At first, we investigated the effects of θ_c and γ on the thrust force when the body of the model is fixed. As a result, we found that the thrust force is maximized when $(\theta_c, \gamma) = (-20°, 40°)$ as shown in Fig. 1(a). Next, we computed the free flight of the butterfly model with this parameter set. As a result, we found that the model can generate not only enough lift force to support an actual butterfly's weight but also enough thrust force to obtain the forward speed comparable to the cruising speed of an actual butterfly as shown in Fig. 1(b).

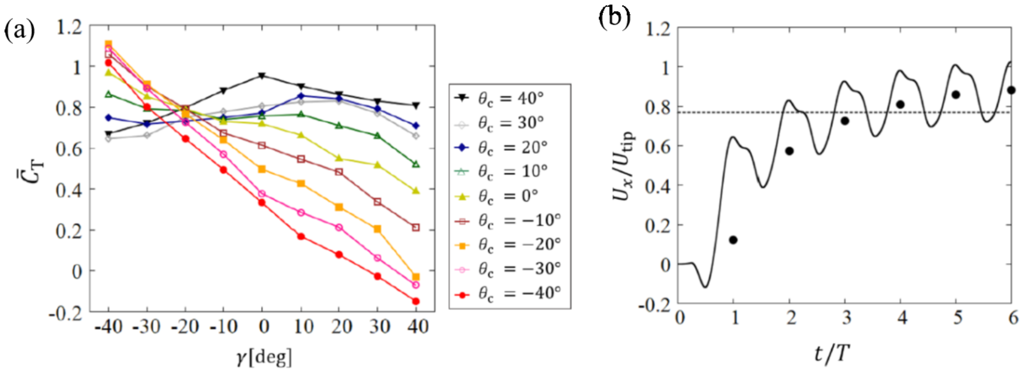


Fig. 1: (a) The thrust coefficient $\overline{C_T}$ averaged in one stroke as a function of the lead-lag angle γ for various centers θ_c of the flapping angle when the body of the butterfly model is fixed, (b) the time variation of the forward speed U_x normalized by the mean wing-tip speed U_{tip}. In (b), the dotted line shows the cruising speed of an actual butterfly (*Janatella leucodesma*), and the bullets indicate the time-averaged value in each stroke.

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Passive Mechanisms Enhance Robustness in Bio-inspired Flight Systems

Hao LIU

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Abstract

Insect and bird size drones – micro air vehicles (MAV) that can perform autonomous flight in natural and man-made environment and hence suitable for environmental monitoring, surveillance, and assessment of hostile situations are now an active and well-integrated research area. Biological flapping-flight system design that has been validated through a long period of natural selection offers an alternative paradigm that can be scaled down in size, but normally brings low-speed aerodynamics and flight control challenges in achieving autonomous flight. Thus, mimetics in bioinspired flight systems is expected to be capable to provide with novel mechanisms and breakthrough technologies to dominate the future of MAVs and drones. Flying insects and birds are capable of actively powering and controlling flights by flapping wings to perform excellent flight stability and maneuverability while presenting passive mechanisms associated with flexible wings and wing-hinges, and deformable bodies. In this talk, with a specific focus on flexibility and robustness strategies in bio-inspired flight systems, I will highlight recent advances and challenges in mathematical methodology and physics in concern with flexible wing aerodynamics, flexible wing-hinge dynamics as well as body flexibility-induced dynamic flight stabilization and flight control in insects and birds as well as in biomimetic flapping MAVs and drones.

References

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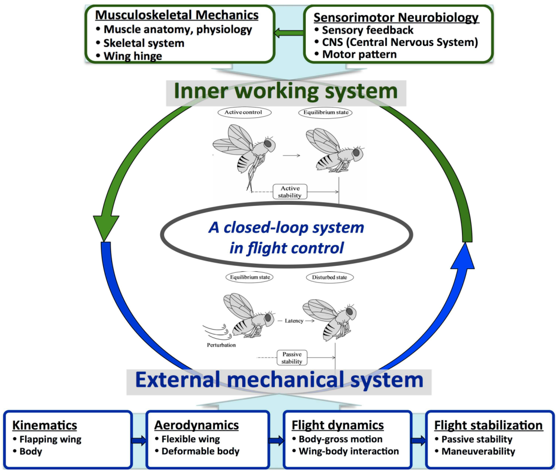

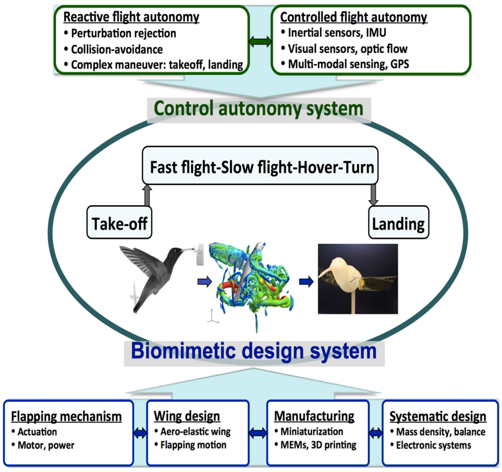

Dynamics and controls of butterflies with experimental observation

Kei Senda[1], Makoto Iima[2], Norio Hirai[3], Naoto Yokoyama[4], and Noriyasu Ando[5]

[1] Kyoto University, [2] Hiroshima University, [3] Osaka Prefecture University,
[4] Osaka University, [5] Maebashi Institute of Technology

Butterflies can maintain desired flapping flights against environmental uncertainties and variations, e.g. gust, weight gain or loss, etc., using their adaptation-capability. Such an adaptive function is considered to emerge from the interaction of the nervous system, body, and environment. We call the adaptive motor function Motion Intelligence or Mobiligence. Controls for stable flight or maneuver are unknown, e.g. how the butterfly moves the wings, etc. The objective of this study is to understand the flight controls of flapping butterflies.

This study investigates these issues by the biological analysis through experimental observations of living butterflies and by the systems biology approach. An experimental system with a low-speed wind tunnel is constructed to measure various flapping flight motions of actual butterflies, *Parantica sita niphonica*. A dynamics model of a living butterfly is derived by Lagrange's method, where the butterfly is considered as a rigid multi-body system. For the aerodynamic forces, an unsteady vortex lattice method (UVLM) is applied. Validity of the mathematical models is shown by an agreement of the numerical result with the measured data.

Using the constructed numerical simulator, a periodic wing kinematics of flapping flight is searched in order to fly the butterfly model. Almost periodic orbits are obtained. In addition, it is shown that the free-vortices in the wakes provide a type of stabilization effect. This research, then, studies how flexibly torsional wings provide a same type of effect on the flight stability. These feedback stabilization effects by interaction of the body and environment can be considered as a low-level control, i.e. a kind of preflex, and named an implicit control.

Because the periodic flapping flight with the implicit controls only is still unstable, some feedback controls are designed for stability as high-level controls, explicit controls, in addition to the implicit controls. As a result, this study suggests the hierarchical control structure with the implicit and explicit controls. Such hierarchic control structures have been found in animals.

At first, two kinds of controllers are designed based on the optimal regulator (LQ) theory. Secondly, steady flights are realized by the simulator, in which the controllers are implemented to the original non-linear system. Stability of the steady flight is analyzed. Thirdly, the latency, that is the time delay to react from external stimulus, exists. A controller considering the latency as the time delay is designed. The above controllers for no time delay become unstable. However, a redesigned controller considering the time delay realizes a stable flight. Finally, maneuvers of butterflies are realized in the simulator for a ramp input. Controls of an actual butterfly and a simulator are discussed by comparing flapping trajectory changes between the experimental observations and the numerical simulations. The numerical simulations are qualitatively similar to the data from an actual butterfly.

This study as well as other biological researches suggests that a designed type of the proposed control structure exists in living butterflies.

Undulatory fish swimming: sources of drag and optimizations of energetics

***Gen Li**
Japan Agency for Marine-Earth Science and Technology (JAMSTEC) , Japan

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Drag is a key factor to explain behaviours and predict strategies in fish. However,drag is extremely difficult to be measured in experiment, and not predicted well by analytical models that ignore the influence of three-dimensional flow and body undulations.

By utilizing an integrated three-dimensional computational approach that couples the Navier-Stokes (NS) equations with the equations of undulating body motion, we decomposed thrust and drag in swimming fish, and obtain the power and cost of transport in fish swimming. We investigated fish in various morphological and kinematic patterns across wide Reynolds number ranges.

We found interesting characteristics of drag in a swimming fish: the (scaling) trend of drag follows that of a three-dimensional object (e.g. 3D sphere and rigid fish body), while the magnitude of drag depends on the kinematics of the undulatory wave, much exceeding that of a rigid fish gliding at the same speed.

The duality in swimming fish determines its swimming strategy. In continuous swimming at a specific speed, fish need to wisely choose its frequency and amplitude to prevent excessive energy consumption due to drag. The amplitude should be neither extremely low nor extremely high, but kept at a certain level. The adjustment of speed is accomplished by frequency change rather than amplitude change, which agrees with existing experimental observations.

Meanwhile, since gliding drag is much less than undulatory drag at the same speed, properly switching between undulatory propulsion and gliding (burst-and-coast) may become a feasible strategy for fish to save energy. Our simulations provide quantitative explanations on the mechanism of the burst-and-coast behavior.

30 Oct (Wed)

Osmotically driven pipe flows: modeling sugar export from a leaf.

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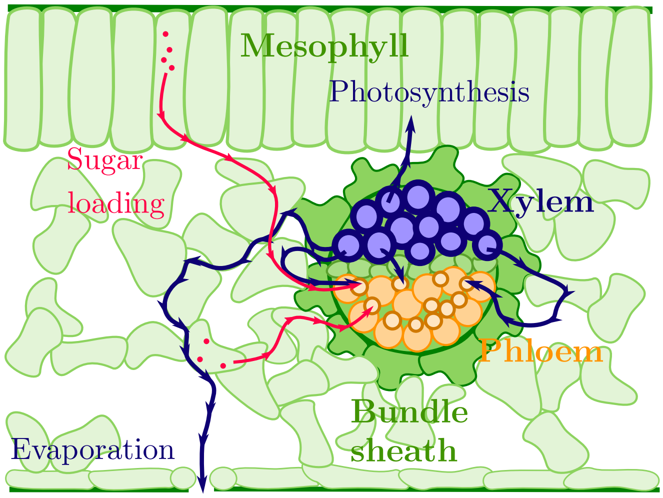
Plant leaves preform an amazing task: to bring in water from the soil, to collect CO_2 from the air, to perform photosynthesis and to export the sugar efficiently. The two parts of the vascular system, the xylem and the phloem, are extremely close to each other in the narrow space of the veins of the leaf, which means that the pressure can drop tens of atmospheres over, say, 5 micrometer. Most of the water which is sucked up from the soil via the xylem under negative pressures evaporates; but a small part is used for photosynthesis and for the sugar transport from the production sites in the mesophyll cells into the phloem tubes and further on to the rest of the plant via the phloem. In the phloem the transport is driven by the osmotic pressure of the sweet sap, and this type of flow has interesting properties, which have not been studied much in the past. In the talk I shall concentrate on the simplest possible venation structure: the linear veins of pine needles. The phloem tubes in a pine needle form a bundle of parallel, porous tubes of almost constant radius and almost constant sugar concentration, and therefore constitute a simple testing ground for the osmotic mechanism. We have recently shown that long needles face a serious problem since the phloem-sap near the tip will be stagnant and no sugar will be exported from there. Correspondingly, most needles are less than around 6 cm - the predicted characteristic length. However, needles that are 30 cm or more do exist, and to understand how they manage, we shall go deeper into the mechanism by which sugar is "loaded" into the phloem tubes.



Cross-section of a leaf

A growth model of a plant root system for bridging the transport function of the root and the root environment

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Plant root system absorbs necessary materials from soil for its growth, and transports some of them to shoot system above ground. At the same time, it plays a critical physiological role as one of main sources of hormones such as Auxin or Abscisic acid. Those hormones are known to regulate the growth of the whole plant system. So far, experimental studies have been made on how tips of root grow in search of water or to avoid pebbles in soil, on how they sense gravity, and so on. However, due to soil in which they grow, data and results were limited in space or time, and little is known about a whole dynamical picture of the root growth and its outcome as mass transport function. Recently, it was revealed in Arabidopsis that there seems Auxin oscillation about the tips which would result in periodic generation of lateral root primordia. This implies that, if one finds a better model to generate such chemical oscillation and connect it with growth, it may possible to reproduce the root system growth and estimate its transport functionality computationally.

In this work, we focus on the plant root system and construct a growth model of the system based on its shape change, hormone productions and transports, absorption of water from the environment. We first construct a pipe model to mimic shape changes of a plant root due to water absorption. We pick three major hormones and implement its chemical reactions and diffusive transportation through cells onto the pipe model. Assigning an appropriate relation between Auxin concentration and pipe growth, and another appropriate threshold for lateral shoot generation, we find a root system reasonably well realised on PC. We demonstrate how the model can mimic an actual example of lettuce root growth in the end.

This talk is based on the collaboration with A. Ogawa (APU), K. Usui (U. Tokyo), and R. Miyake (U. Tokyo).

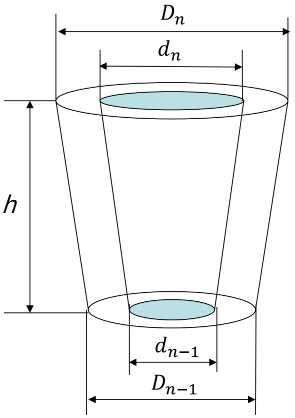

Fig. 1 An element of the pipe model

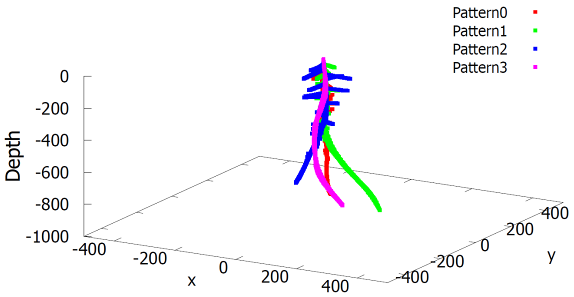

Fig. 2 Simulated roots and influence of Auxin on its growth

Hydrodynamic model of biological tissues: tissue growth and skin cancer

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On long time scale the neighbors of a cell in a tissue change due to cell divisions and cell deaths. This structure rearrangement is manifested by a slow velocity field that resembles flow in a viscous fluid.[cite Paris school 2009 PNAS].

In this talk first a derivation of the force balance equation is first presented, the goal is to connect the usual macroscopic parameters such as elastic modulus and viscous coefficients to parameters that are related to cell scale events, for example cell division rate, cell death rate, and force involved during such processes. This connection invites experimental measurements to test the validity of coarse grained description of tissue dynamics.

After establishing a macroscopic approach to tissue dynamics, the growth of a monolayer tissue in a minimal model is discussed. It is found that due to spatially varying cell differentiation rate, the pressure field and flow field around the boundary of proliferative cell niche show a distinctive change. Furthermore, in a growing tissue the flow field away from the growing front does not change in time. The final steady state distribution of proliferative cells and differentiated cells depend on the differentiation and proliferative rates, and the parameter regime in which these distributions are similar to experimental observation is identified.

Finally, the model is extended to describe the growth of skin cancer. Here the conventional model H for macrophase separations is extended to include the growth of cancer cells and a mechanical friction between dermis and epidermis. Interestingly a nonequilibrium microphase separation due to the proliferation of cancer cells is found by numerically solving the time evolution equations of the system. The phase separation kinetics strongly depends on the cell proliferation rate as well as on the strength of hydrodynamic interactions. A steady-state diagram of cancer patterns is established in terms of these two dynamical parameters and some of the patterns correspond to clinically observed cancer patterns. Examining the time evolution of the average composition of cancer cells and the characteristic length of the microstructures reveals that different sequence of cancer patterns can be obtained by changing the proliferation rate and/or hydrodynamic interactions

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[2] Pattern formation of skin cancers: Effects of cancer proliferation and hydrodynamic interactions T. Hoshino, M.W. Liu, K.-A. Wu, H.-Y. Chen, T. Tsuruyama and S. Komura, Phys. Rev. E, 99, 032416 (2019).

Left-right asymmetric aggregation in *Chlamydomonas*

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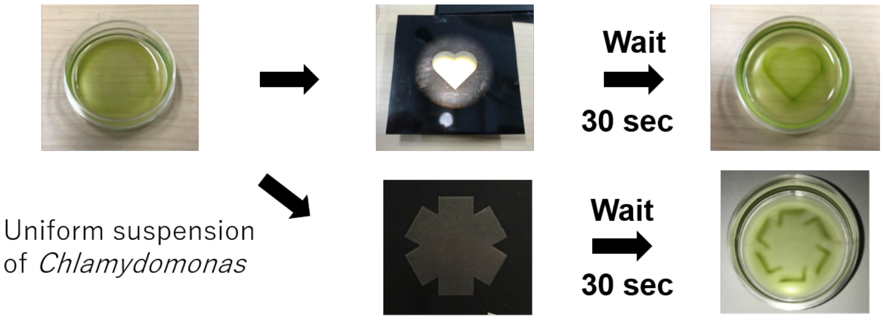
Chlamydomonas reinhardtii is a unicellular green alga, and one of the well-studied model organisms. This species has two anterior flagella and swims by using a breast-stroke motion of the flagella. This guy also has an eyespot near its equator, at which they can receive a light and change the direction of their swimming by changing the stroke motion of the left and right flagella. This behavior is called phototaxis, and important for their life, because they conduct photosynthesis. Recently, we have conducted a simple experiment about their response to the light. In a usual situation *Chlamydomonas* swims toward the direction of incident light, so they gather in a brighter region in space. But if the space has some sharp boundary between bright and dark regions, *Chlamydomonas* tends to gather at that boundary more frequently. That is, if you make a mask that has both transparent regions and opaque regions, and illuminate a petri dish that contains a *Chlamydomonas* suspension through the mask, you will get an aggregation pattern of *Chlamydomonas* where the places corresponding to the boundaries between transparent and opaque regions of the mask have a high concentration of *Chlamydomonas* and looks deep green in color. This mechanism of this aggregation at the bright-dark boundary is still unclear. In addition to this behavior, more interestingly, this aggregation pattern exhibits some left-right asymmetry, i.e., while the shape drawn in the mask and experimental set up are completely symmetric, the aggregation pattern appearing in the dish has some asymmetry. We shall approach this phenomenon from both experimental and theoretical sides by conducting direct observation of movement of *Chlamydomonas* and making a simple mathematical model for describing their individual movement.



Scaling laws of the leading-edge vortices

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Small flapping fliers including insects, small birds and biomimetic micro-air vehicles (MAVs) alike, have thin wings with sharp edges. As the wings move, air flow separates from the leading edges and forms strong vortices that remain attached on the wings during most part of the flapping cycle, producing pressure deficit in the regions adjacent to the leading edges. The aerodynamic force is thus enhanced. This “stable” leading-edge vortex (LEV) is one of the main reasons why flapping wings have larger lift coefficient than commonly admitted in the fixed-wing aerodynamics.

LEVs on flapping wings are unsteady and three-dimensional. The unsteady effects are essential during the “rotation” after upstroke and downstroke. However, during the “translation” in the middle of an upstroke or a downstroke, when the forces are maximized, the LEV nominally attains its equilibrium steady state. The latter has been examined using a rotating flat plate as a simplified model. Numerical simulations using the computational fluid dynamics approach show that wings of different shape produce remarkably similar conical leading-edge vortices, if the chord length is large enough to support the flow reattachment line, when the Reynolds number is in the range from a few hundred to thousands. After postulating that an equilibrium state of the vortex is maintained by the competing effects of vorticity production at the leading edge and its three-dimensional transport in the presence of spanwise flow and downwash, it is straightforward to derive a low-order model. The problem is solved analytically, providing closed-form expressions for the circulation and the vortex centroid position (D. Chen, D. Kolomenskiy, R. Onishi and H. Liu, Versatile reduced-order model of leading-edge vortices on rotary wings, *Phys. Rev. Fluids*, **3**, 114703, 2018).

The model explains how the design parameters such as the aspect ratio of the wing, the angle of attack and the Reynolds number can be used to control the properties of the vortex. In particular, a short formula has been derived for the circulation Γ versus radial distance from the axis of rotation r. When the angle of attack is approximately equal to 45 degrees and the Reynolds number is large, the equation for the circulation takes a particularly simple form $\Gamma_{45^\circ} = 2\,\Omega\, c^{2/3}\, r^{4/3}$, where Ω is the angular velocity and c is the chord length.

Kinematic Analysis of Periodic Motion using Accelerometer and Gyroscope

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By recent development of measurement devices, it becomes easier to obtain data of many kinds animal behavior performed out of laboratories. Bio-logging methods with various type of sensors enable us to exhibit several aspects of remote objects, such as the geolocation, (ultra-)sounds, a temperature, a heartbeat rate and so on. Especially, the combination of an accelerometer and a gyroscope is useful to access to the kinematic aspect of the object motion.

In this study, we focus on a periodic motion of biological objects. By time series analysis of kinematic data obtained from tri-axial accelerometer and tri-axial gyroscope attached to them, we suggest a method to estimate the position of motion “axis”: the least moving point during one cycle.

We apply this method to experimental data of human walking and running state on a treadmill with varying speed. The walk-run transition process is characterized from a kinematic viewpoint. The participants (N=21) are classified into two groups by the location of axis in their running state.

Phase reduction of flapping flight and swimming

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Many animals, from microorganisms to albatrosses and whales, swim or fly through their periodic motion of their fins and wings. Regardless of the Reynolds number, their motions are achieved by periodic flows. The periodicity enables us to reduce their dynamics to a simplest one with single characteristic variable called phase, which has been known as the phase reduction theory. The phase reduction theory has been applied to many problems, typically to analyze the synchronization phenomena, e.g. flashing fireflies or large-amplitude wobbling of London Millennium bridge due to the stepping of the pedestrians. In the field of biofluid mechanics, the phase reduction theory has been applied to the synchronization of flagella, but further application to full system consisting of wings/fins motion and surrounding fluid, such as insect flight or fish swimming, has not been achieved, despite that such application will give us much information, especially for the stability and controllability.

In this presentation, I will discuss the possibility of phase reduction theory on biofluid mechanics based on two recent studies [1,2]. First, it will be shown that the vortex structure generated by heaving wing in a uniform flow can be controlled by a short-time change of wing motion corresponding to the phase shift [1]. Second, I will show that the computational cost needed to derive full information of the phase response property can be significantly reduced by a new calculation algorithm [2]. Such algorithm is needed for future application of the phase reduction to flight/swimming problems. The phase response property of the Kármán's vortex street will be analyzed as a demonstration.

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