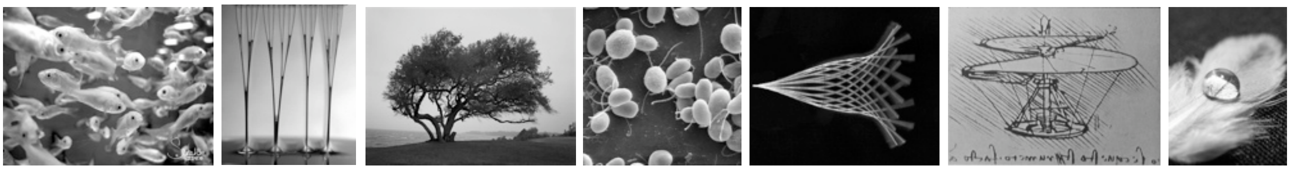
Fluid & Elasticity 2009



Fluid & Elasticity 2009

June 23-26, 2009
Carry-le-Rouet, France

irphe Institut de Recherche sur les Phénomènes Hors Équilibre

Université de Provence Aix-Marseille I

Université Paul Cézanne Aix-Marseille III

Dantec Dynamics

Program

Tuesday, June 23

9:00 – 9:30 Registration and opening talk

9:30 – 10:10 Aeroelasticity I (Chair: M. Shelley)

- F. J. Huera-Huarte
  Vortex modes in the wake of flexible circular cylinders with POD and fuzzy clustering
- E. Duarte Gutierrez, M. E. Marin Mejia, A. Cros
  Membrane oscillation under periodic excitation

10:10 – 10:40 Coffee break

10:40 – 12:00 Aeroelasticity II (Chair: M. Shelley)

- N. Favrie, S. L. Gavrilyuk, R. Saurel
  Diffuse solid-fluid interface model in cases of extreme deformations
- P. Buchak, P. M. Reis, C. Eloy, J. Bush
  The clapping book: wind-driven oscillations in a stack of elastic sheets
- F. Gosselin, E. de Langre
  Drag reduction by reconfiguration of flexible plates
- P. Sváček, M. Feistauer, J. Horáček
  On comparison of laminar and turbulent flow models in aeroelastic problems with large amplitudes

12:00 – 14:30 Lunch break

14:30 – 15:15 Invited speaker (Chair: E. Lauga)

- A. E. Hosoi
  Optimizing low Reynolds number locomotion

15:15 – 16:35 Microswimming I (Chair: E. Lauga)

- A. Andersen, T. Bohr, H. H. Jakobsen, T. Kiørboe , V. J. Langlois
  Hydrodynamics of attacking, swimming, and escaping copepods
- D. Saintillan
  The rheology of active particle suspensions: kinetic theory
- N. Coq, O. du Roure, M. Fermigier, D. Bartolo
  Helical beating of an elastic filament
- K. Drescher, K. Leptos , I. Tuval, T. Ishikawa, T. J. Pedley, R. E. Goldstein
  Dancing Volvox : Hydrodynamic bound states of swimming algae

16:35 – 17:05 Coffee break

17:05 – 18:45 Microswimming II (Chair: A. Hosoi)

- O. du Roure, A. Babataheri, M. Roper, M. Fermigier
  Tethered fleximags as artificial cilia
- E. Lauga
  Propulsion by surface distortion in complex fluids
- M. Polin, I. Tuval, R. Goldstein
  Flow induced flagellar synchronization in Volvox carteri
- D. Bartolo, E. Lauga
  Collective locomotion of soft active particles
- E. Wandersman, O. du Roure, A. Lindner, M. Fermigier
  Buckled in translation

Wednesday, June 24

8:00 – 8:45 Invited speaker (Chair: T. J. Pedley)

- M. Shelley
  Microscale instability and mixing in driven and active complex fluids

8:45 – 10:05 Biomechanics I (Chair: T. J. Pedley)

- M. Argentina, L. Mahadevan
  A model describing fish locomotion
- S. Chatkaew, M. Georgelin, M. Leonetti
  Unbinding dynamics of lipidic membrane near a substrate
- J. D. Eldredge, J. Toomey, M. M. Wilson, D. Pisani
  High-fidelity computational studies of canonical problems in biomorphic locomotion
- R. Godoy-Diana
  Experimental studies on model flapping-wings

10:05 – 10:35 Coffee break

10:35 – 11:55 Biomechanics II (Chair: T. J. Pedley)

- A. Leroyer, M. Visonneau, M. Porez, F. Boyer
  Eel-like body swimming : extension of the elongated body theory of Lighthill, RANSE simulations and optimisation
- P. Marmottant
  Study of the ultrafast trap of an aquatic carnivorous plant
- X. Noblin, J. Westbrook, M. Argentina, J. Dumais
  Biomechanics of fern spores discharge
- J. Walter, A.-V. Salsac, D. Barthès-Biesel
  Motion of a capsule in a simple shear flow: Coupling of finite element and boundary integral methods

11:55 – 16:00 Lunch break

16:00 – 16:45 Invited speaker (Chair: M. Heil)

- A. Bottaro
  Hairfoils: passive actuators for flow control

16:45 – 18:45 Compliant walls (Chair: M. Heil)

- E. J. Brambley
  The fluid-solid boundary condition for uniform flow over a compliant surface
- C. Brücker
  Near wall turbulence control via flexible micro-hairs
- J. Hoepffner, A. Bottaro, J. Favier
  Transient mechanisms in fluid systems with elasticity
- A. D. Lucey, M. W. Pitman
  Eigen-analysis of fluid-loaded compliant panels
- M. Hosseini, S. A. Fazelzadeh
  Fluid-Elastic interaction of spinning functionally graded thin-walled pipes conveying high temperature flow
- A. Song, K. Breuer
  Vortex-induced flapping and twisting of a compliant plate

20:00 Special dinner

Thursday, June 25

8:00 – 8:45 Invited speakers (Chair: J. Bush)

- B. Roman, J. Bico
  Capillarity and elasticity

8:45 – 10:05 Capillarity and Drops I (Chair: J. Bush)

- A. Antkowiak, C. Josserand
  Dynamical origami
- M. Piñeirua, B. Roman, J. Bico
  Actuating capillary origami with electrowetting
- E. de Langre, C. N. Baroud, P. Reverdy
  Energy criteria for elasto-capillary wrapping
- H. Lhuissier, E. Villermaux
  Soap films burst like flapping flags

10:05 – 10:35 Coffee break

10:35 – 12:15 Capillarity and Drops II (Chair: J. Bico)

- R. E. Pepper, L. Courbin, H. A. Stone
  Splashing on elastic membranes: The importance of early-time dynamics
- J. W. Bush, S. Jung, C. Clanet
  Spider capture thread: form and function
- A. Ponomarenko, C. Clanet, D. Quéré
  Falling drops over elastic sheets
- P. M. Reis, S. Jung, C. Clanet, J. Bush
  Grabbing water with thin elastic sheets: the elasto-pipette
- N. Vandenberghe, R. Vermorel, E. Villermaux
  Impacts on thin elastic sheets

12:15 – 15:00 Lunch break

15:00 – 15:45 Invited speaker (Chair: S. Alben)

- E. de Langre
  Plant dynamics under wind load: strategies and solutions

15:45 – 16:45 Flow-Induced Vibration I (Chair: S. Alben)

- S. Michelin, S. G. Llewellyn Smith
  Flapping of flexible membranes in high-Re flows and applications to locomotion
- O. Doaré
  Effect of dissipation on local and global stability of a fluid conveying pipe
- W.-X. Huang, H. J. Sung
  Three–dimensional simulation of a flapping flag in a uniform flow

16:45 – 17:15 Coffee break

17:15 – 18:35 Flow-Induced Vibration II (Chair: E. de Langre)

- S. Alben
  The flapping-flag instability as a nonlinear eigenvalue problem
- A. Manela, M. S. Howe
  The motion and sound of a forced flag
- B. Ricaud, P. Guillemain, J. Kergomard, F. Silva, C. Vergez
  Bifurcations and periodic regimes in woodwind instruments
- P. Šidlof, O. Doaré, A. Chaigne
  Flow separation in flow-induced vibration of human vocal folds

Friday, June 26

8:30 – 9:15 Invited speaker (Chair: A. Bottaro)

- M. Heil
  Theoretical and computational analysis of flow in collapsible tubes

9:15 – 10:35 Internal Flows I (Chair: A. Bottaro)

- M. Astorino, F. Chouly, M. A. Fernandez
  An added-mass free semi-implicit coupling scheme for fluid-structure interaction arising in blood flows
- J. D. Berry, M. C. Thompson, J. Carberry
  Characterisation of the forces and deformation experienced by an adhered cell
- F. Gallaire, V. Duclaux, C. Clanet
  A mechanical view on abdominal aortic aneurysms
- A. Juel, A. Heap
  Anomalous bubble propagation in elastic tubes

10:35 – 11:05 Coffee break

11:05 – 12:05 Internal Flows II (Chair: A. Bottaro)

- R. Kudenatti, N. M. Bujurke, T. J. Pedley
  Oscillations and instability of high-Reynolds-number flow in a collapsible channel
- D. Pihler, T. J. Pedley
  A quasi-one-dimensional model for collapsible channel oscillations
- H. Woolfenden, M. Blyth
  Transit of an elastic capsule through a branching channel

12:05 Closing ceremony

12:15 Lunch

Aeroelasticity

Vortex modes in the wake of flexible circular cylinders with POD and Fuzzy clustering

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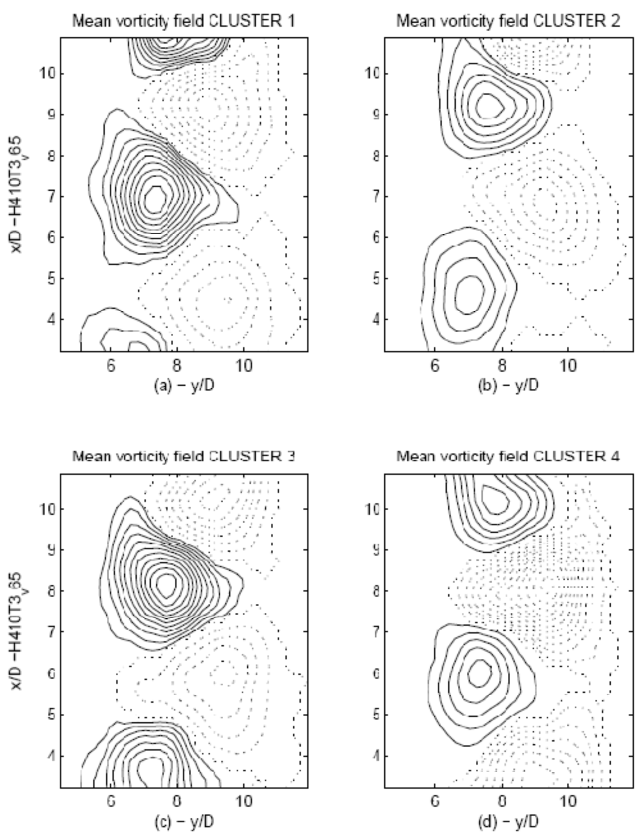
A method combining Proper Orthogonal Decomposition (POD) and Fuzzy Clustering (FC) has been used for pattern recognition, in order to identify vortex modes in digital image particle velocimetry (DPIV) data obtained in the wake of a long flexible circular cylinder undergoing vortex-induced vibrations. The POD allows a low dimensional description of the wake, so the fuzzy c-means algorithm can be used for clustering analysis. The output is a set of well defined vorticity clusters representing the vortex patterns found in the wake. The figure shows the mean vorticity fields of the 4 clusters obtained in one of the runs for which the analysis was performed. All clusters in the figure indicate the main structure consisted of the classical Karman vortex street (2S mode).

The DPIV data was obtained at two elevations along the length of a long flexible circular cylinder model, which had an aspect ratio of about 94. The experiments were carried out in a water channel with flow speeds up to 0.75 m/s, giving Reynolds numbers in the range from 1200 to 12000. The set up allowed changes in the fundamental natural frequencies, which resulted in reduced velocities based on that frequency, up to 16. The mass ratio of the model, mass divided by mass of displaced parameter about 0.05. The analysis has been extended to more than 65 runs.



Membrane oscillation under periodic excitation

E. Duarte Gutierrez, M. E. Marin Mejia, A. Cros
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We present in this work the dynamical behaviour of an elastic membrane submitted to a periodic oscillation of its axis. The elastic membrane is constituted by a paper which is maintained by an edge to a cylindrical axis. A periodic motion can be given via a motor to this axis, whose frequency can be controlled by the operator.
The motion is recorded via a video camera and the amplitude is measured as a function of the axis frequency. This curve permits to find the natural modes of the elastic membrane as predicted by the theory (see [1, 2] for example).
After that, the same analysis is performed when the elastic membrane is submitted to an air flow. An interesting comparison with the dynamical characteristics of the membrane without excited vibration [3] will be done.

[1] J. Dugundji, B. Perkin and E. H. Dowell. Subsonic Flutter of Panels on Continuous Elastic Foundations - Experiment and Theory. *M.I.T. Aeroelastic and Structures Research Laboratory* (1962).
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[3] M. P. Païdoussis. Fluid-Structures Interactions - Slender Structures and Axial Flow, Vol. 2. London: Academic Press (2004).

Diffuse solid-fluid interface model in cases of extreme deformations

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2 also Institut Universitaire de France

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A diffuse interface model for elastic solid - fluid coupling in Eulerian formulation is built. This formulation generalizes the diffuse interface models for compressible multi-fluid computations ([5], [7], [1], [8], [9]). Elastic effects are included following the Eulerian conservative formulation proposed in [3],[6],[4],[10],[2]. The aim of this paper is to derive an extended system of hyperbolic partial differential equations, valid at each mesh point (pure fluid, pure elastic solid, and mixture cells) to be solved by a unique hyperbolic solver. The model is derived with the help of Hamilton's principle of stationary action. In the limit of vanishing volume fractions the Euler equations of compressible fluids and a conservative hyperelastic model are recovered. The model is hyperbolic and compatible with the entropy inequality. Special attention is paid to the approximation of geometrical equations, as well as the fulfillment of solid-fluid interface conditions. Capabilities of the model and methods are illustrated on hypervelocity impacts of solids.

References:

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The Clapping Book: wind-driven oscillations in a stack of elastic sheets

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We present the results of a combined experimental and theoretical investigation of the dynamics of a book clapping in the wind. In our experiments, a steady horizontal air stream blows across an initially horizontal stack of paper, clamped at the downstream end. Pages lift off to form a growing bent stack of pages whose shape is determined by the balance of aerodynamic forces, elastic resistance to bending, and gravity. As more pages lift off to join the bent stack, the increasing importance of elasticity eventually causes the book to clap shut. Upon returning to its initial state, this process repeats, resulting in continuous oscillations with a well-defined period. In figure 1 we show one period of this clapping motion.

We model the bent stack of pages as an elastic sheet at equilibrium in a steady two-dimensional flow. We use the Euler-Bernoulli beam equations for the sheet coupled with a description of the fluid force based on slender body theory. From this we determine how many pages a given wind speed can support. We also attempt to model the rate at which pages lift off from the flat stack of paper before they join the bent stack. Combining the calculation of the bent stack size with the description of page liftoff allows us to predict the period of the clapping motion.

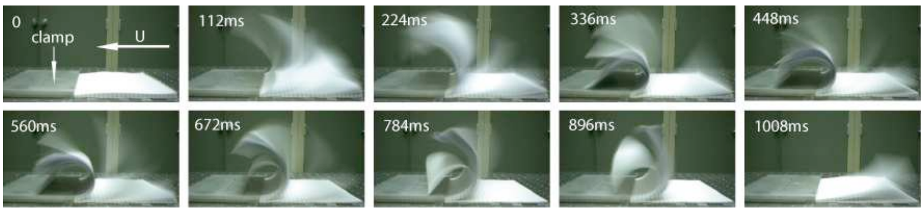

Figure 1: Time sequence of snapshots of the *clapping motion* of a partially clamped block of sheets, for a single period. The air-flow points from the right to the left of the block. The respective time (in μs) is shown in each frame.

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Drag Reduction by Reconfiguration of Flexible Plates

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By bending and twisting under fluid loading, plants reduce their projected area perpendicular to the flow and also become more streamlined [1]. Through reconfiguration, the drag load plants must support does not grow with the square of the velocity of the flow they are subjected to – as it would on a rigid bluff body – but rather more slowly. It was shown with systems of simple geometries like flexible fibres in soap film by [2], and disks rolling into cones in water flow by [3] that the reconfiguration can be quantified and an asymptotic case of large deformation existed.

Continuing in this direction, we propose an experimental investigation in air on the drag of flexible plates of simple geometries combined with a theoretical modelling of their deformation. In Fig. 1 (a), the superimposed photographs of the typical deformation of a rectangular specimen at increasing flow velocity are shown. The behaviour of the plate folding in the flow is well captured by a simple model using the Euler-Bernoulli equation for the large deflection of a beam coupled with an empirical drag formulation in Fig. 1 (b). Through extensive wind-tunnel testing, the dimensionless parameters that characterise the problem are found. Scaling the drag by that of an equivalent rigid one and scaling the dynamic pressure by the bending rigidity of the plate, the drag data of 20 rectangular specimens is collapsed onto a single curve in Fig. 1 (c). The drag reduction of the specimen is well reproduced by the model shown in solid line in Fig. 1 (c).

The velocity dependence of the drag in the asymptotic case where the deformation is very large found by [2] and [3] with their theoretical model are shown to be obtainable through a simple dimensional analysis. However, it is shown that in all experiments, the asymptotic regime is never reached.

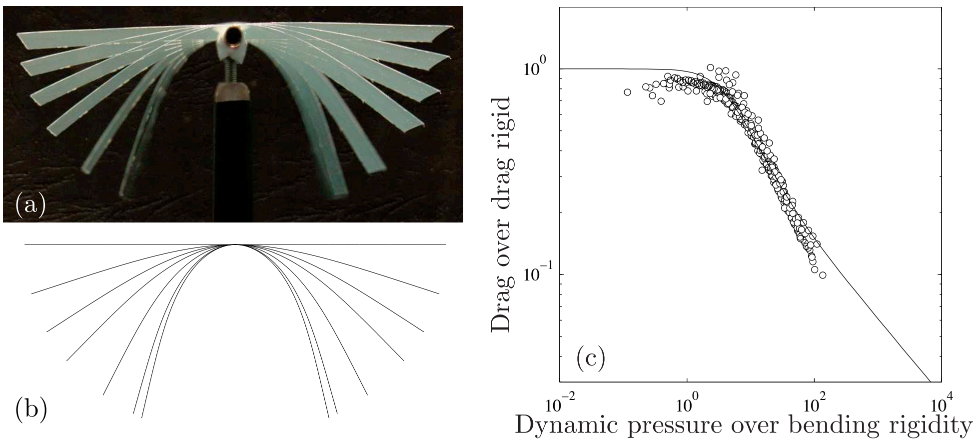

Figure 1: (a) Superimposed photographs of the deformation of a rectangular specimen and (b) corresponding modelled shapes. (c) Comparison between model and experiments of the effect of the flexibility on the drag of rectangular flat plates.

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On comparison of laminar and turbulent flow models in aeroelastic problems with large amplitudes

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Abstract

In this paper we focus on a problem of mutual interaction of a two dimensional fluid flow and a moving airfoil. The viscous incompressible flow is considered, and the interaction with the airfoil with two or three degrees of freedom (airfoil bending, rotation, and aileron rotation) is modelled. The problem is mathematically formulated and the numerical approximation of the coupled problem is described. The attention is paid to geometrical nonlinearities.

Particullary we shall also focus on the comparison of two flow models: laminar or turbulent. The fluid motion is either described by the incompressible Navier-Stokes equations (laminar model) or Reynolds Averaged Navier-Stokes equations (RANS) and coupled with a turbulence model (Spalart-Allmaras and k-omega). The numerical approximation is performed by the finite element method stabilized with Streamline Upwind/Petrov-Galerkin(SUPG) with pressure stabilizing Petrov-Galerkin(PSPG) method and grad-div stabilization, cf. [2]. In order to allow the computation on moving meshes, the Arbitrary Lagrangian-Eulerian method is used, cf. [3]. The stabilization of the finite element method then needs to be modified in a consistent way, cf. [1].

The structure motion is described by a system of ordinary differential equations, where the geometrical nonlinearities appear due to the consideration of large amplitudes. The system of differential equations includes the aerodynamical forces obtained from the flow model and the airfoil motion results in deformations of the computational domain. In the computation a strong coupling algorithm is employed for the solution of both flow and structure models.

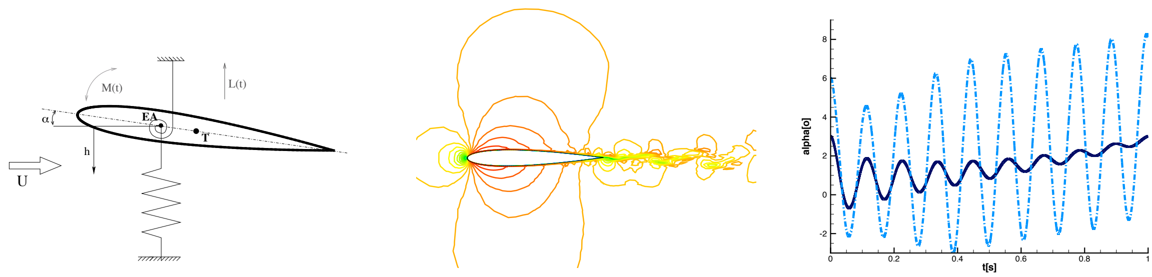

Figure 1: Elastic support (left) of NACA 0012, instantenous fluid velocity isolines (laminar model) around moving NACA 0012 (middle), the dependence of the angle of rotation on time in the aeroelastic response of the system (different initial condition, post-critical far field velocity $U_\infty = 40\,\mathrm{m\,s^{-1}}$) (right).

The developed numerical method was applied to aeroelastic problems. The simulation was performed for a far field velocity close to the critical velocity of the aeroelastic system and also for a post-critical velocity.

References

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Microswimming

Optimizing Low Reynolds Number Locomotion

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Biological systems exhibit multiple modes of Low Reynolds number locomotion from swimming to crawling to digging. In this talk I will address a subset of these strategies and discuss ways in which we can take inspiration from nature to advance technology. The key concept behind bio-inspired design is that, if a structure exists in nature that performs a desired function, it has often been "optimized" in some sense and it is difficult for engineers to dramatically improve upon the natural design. Yet, historically, the countless failures in biomimetics have been more notorious than its successes (e.g. airplanes with flapping wings). There are many reasons for these failures -- impractical energy requirements and complexity of controls, among others. To avoid these pitfalls, our biomimetic studies focus on simple biological systems (preferably organisms with primitive or, better yet, non-existant central nervous systems) in which the energy requirements are low and the biological solutions to challenging questions are grounded in mechanics rather than in neurological controls.

Beyond the general challenges associated with optimization and design, there are a number of issues that are unique to low Reynolds numbers locomotion strategies. At small scales, the fluid equations of motion are linear and time-reversible, hence reciprocal motion -- i.e., strokes that are symmetric with respect to time reversal -- cannot generate any net translation (a limitation commonly referred to as the Scallop Theorem). There are a number of ways to get around the Scallop Theorem including carefully chosen morphologies and kinematics, exploiting geometric nonlinearities that arise near soft surfaces, or capitalizing on nonlinear rheological properties of the surrounding media.

One symmetry-breaking solution commonly employed by eukaryotic microorganisms is to select nonreciprocal stroke patterns by actively generating torques at fixed intervals along the organism. Hence, we will address the question: For a given morphology, what are the optimal kinematics? In this talk we present optimal stroke patterns using biologically inspired geometries such as single-tailed spermatozoa and the double-tail morphology of Chlamydomonas, a genus of green alga widely considered to be a model system in molecular biology. In the later, we find that the two optimal beat patterns revealed in numerical studies that maximize swimming efficiency and nutrient uptake qualitatively match the commonly observed beat patterns in live Chlamydomonas.

In locomotion studies, the geometry of the system cannot be decoupled from the kinematics, hence the two must be optimized simultaneously. For spermatozoa, we find that if geometry and kinematics are optimized concurrently, predicted optimal tail lengths match those observed in mammalian sperm across a wide range of species.

Hydrodynamics of Attacking, Swimming, and Escaping Copepods

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Copepods are small crustaceans and as the most abundant zooplankton in the oceans they play a crucial role in pelagic food webs. Copepods swim to find food and mates and to escape encountered predators. But swimming has costs in terms of both energetic expenditure and of an elevated risk of encountering a predator. This latter risk is partly due to the fact that a swimming or escaping copepod creates a fluid disturbance that makes it "visible" to predators with hydrodynamical perception capability. Motility patterns vary widely among copepods: some species hardly move at all while others cruise more or less constantly at high speed. To understand the diversity in motility patterns and their adaptive value one need not only to be able to assess the advantages of different motility patterns, but also the expenses. Using high-speed video we have recorded attack and jump sequences and extracted kinematics of freely swimming copepods. In this talk I will address the following questions using our experimental observations and analytical modelling:

1. Copepods can perform attack jumps when a motile prey is perceived. What is the water flow that the copepod creates in an attack jump, and how does the copepod avoid pushing away the prey?

2. Copepod swimming kinematics consists of series of small jumps. What is the cost of locomotion, i.e., what is the power required for the copepod to move the swimming legs and jump, and how does energetic requirements scale with size and speed?

3. Copepods may make very strong escape jumps and move 50 body lengths away when they are disturbed by a predator. What is the hydrodynamics of escape jumps, and how big and stable are the hydrodynamic disturbances (vortices) that the copepod leaves behind in its wake?

THE RHEOLOGY OF ACTIVE PARTICLE SUSPENSIONS: KINETIC THEORY

David Saintillan
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A kinetic model was developed and applied to study the shear rheology of a dilute suspension of self-propelled particles, such as swimming microorganisms. In this model, valid in the limit of infinite diluteness (negligible particle-particle interactions), the swimmers are represented as prolate axisymmetric particles with director $\mathbf{p}$, which exert a force dipole of magnitude σ_0 on the surrounding fluid as they swim, with $\sigma_0 > 0$ for puller particles and $\sigma_0 < 0$ for pusher particles [1]. The particles are placed in an externally applied velocity gradient $\nabla\mathbf{u}$ with rate-of-strain tensor E and vorticity tensor W. Extending the classic theory of Hinch & Leal [2] for suspensions of passive rods, the effective stress tensor is given by the sum of the Newtonian stress in the suspending fluid and of an extra particle stress:

$$\mathbf{\Sigma} = -p\mathsf{I} + 2\eta_0\mathsf{E} + \mathbf{\Sigma}^p, \tag{1}$$

where the particle stress is calculated as a configuration average of the force dipoles on the suspended particles [3], which include contributions from swimming (permanent dipole σ_0), from the external flow, and from Brownian motion (if applicable):

$$\mathbf{\Sigma}^p = n\langle\sigma_0\,(\mathbf{pp} - \mathsf{I}/3)\rangle + n\langle A(\mathbf{p}\cdot\mathsf{E}\cdot\mathbf{p})\,(\mathbf{pp} - \mathsf{I}/3)\rangle + n\langle 3kT\,(\mathbf{pp} - \mathsf{I}/3)\rangle, \tag{2}$$

where n is the number density in the suspension, and the constant A depends on the precise shape of the particles and may be evaluated based on slender-body theory. In equation (2), $\langle\cdot\rangle$ denotes averaging with respect to the orientation distribution $\Psi(\mathbf{p},t)$. This distribution satisfies a Fokker-Planck equation including the effects of the external flow, angular diffusion (with rotary diffusivity d_r), and particle tumbling (with a characteristic correlation time scale τ):

$$\frac{\partial\Psi}{\partial t} + \nabla_{\mathbf{p}}\cdot(\dot{\mathbf{p}}\Psi) - d_r\nabla^2_{\mathbf{p}}\Psi + \frac{1}{\tau}\left(\Psi - \frac{1}{4\pi}\right) = 0 \tag{3}$$

where $\dot{\mathbf{p}}$ denotes the angular velocity of a particle resulting from the applied shear flow.

To calculate the particle extra stress, equation (3) for the orientation distribution was solved numerically using a spectral decomposition of $\Psi(\mathbf{p},t)$ on the basis of surface harmonics and a semi-implicit second-order time-marching scheme. The particle stress tensor was then determined, and results for the effective steady-shear viscosity and normal stress differences as functions of the dimensionless flow strength $\mathrm{Pe} = \dot\gamma/d_r$ and dimensionless correlation timescale τd_r will be presented, where the case of pusher particles ($\sigma_0 < 0$) and puller particles ($\sigma_0 > 0$) are shown to exhibit very different rheological behaviors. The case of unsteady shear will also be studied, and we will conclude by discussing the possible effects of particle-particle interactions on active suspension rheology, in the light of the recent analysis of [1].

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Helical beating of an elastic filament

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At the microscale, the absence of inertia causes any reciprocal sequence of motions to produce no net thrust. As a consequence, the two most standard propulsion strategies used by microorganisms are the oscillation of flexible flagella and the rotation of rigid helices. We focus here on an intermediate mechanism, where a long flexible filament is rotated in a viscous fluid with a tilt from the rotation axis. The competition between viscous stresses and elastic forces bends the filament into a chiral shape, and this induced helicity generates a propulsive force along the axis of rotation. We analyze experimentally the shape of such a rotating filament [1]. As the rotation speed increases, the filament undergoes a continuous but sharp transition from a barely deformed shape to a tight helix collapsing on the rotation axis. We characterize this transition with two geometrical parameters, quantifying the wrapping around and the collapse on the axis of the filament. Interestingly, this wrapping transition is associated with an unstable branch in the axial force versus axial torque relation, in agreement with other numerical or experimental work [2, 3]. However, the axial force versus effective transverse torque relation is monotonous. We use a simple linear model to describe the fluid-structure interaction, which correctly accounts for the non linear features of the force-torque relations. This allows us to give new physical insight on the filament dynamics. Particularly, we reveal their strong dependance on the actuation mode and on the anchoring conditions [4].

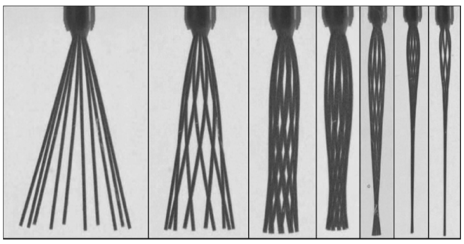

Fig. 1 – Superposition of snapshots of the filament taken over one rotation period, with a constant time interval. From left to right : as the rotation speed increases, the filament wraps itself and collapses on the rotation axis.

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Dancing *Volvox*: Hydrodynamic Bound States of Swimming Algae

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The spherical micro alga *Volvox* swims by means of flagella on thousands of surface somatic cells. This geometry and its large size make it a model organism for the fluid dynamics of multicellularity. Remarkably, when two nearby *Volvox* spheroids swim close to a solid surface, they are attracted together and can form stable bound states in which they "waltz" or "minuet" around each other. A surface-mediated hydrodynamic attraction combined with lubrication forces between spinning, bottom-heavy *Volvox* explains the formation, stability and dynamics of the bound states. These phenomena are suggested to underlie observed clustering of colonies at surfaces.

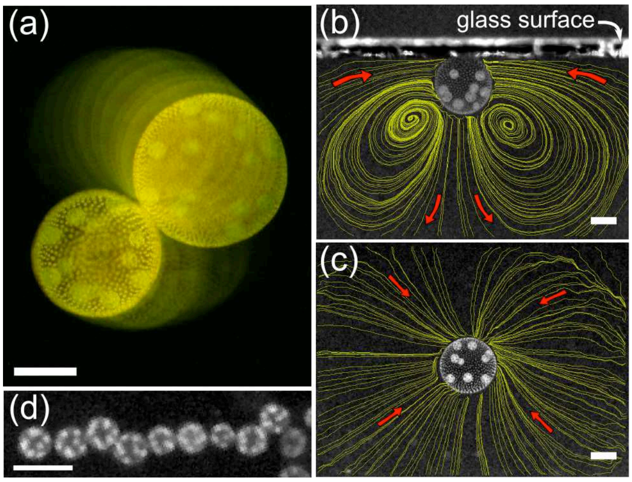

FIG. 1: (a) Top view of a pair of *V. carteri* spheroids, waltzing around each other. Superimposed images were taken 4 s apart, and graded in intensity. (b) Side, and (c) top views of a spheroid swimming against a horizontal coverslip, with fluid streamlines determined from particle imaging velocimetry. Scales are 200 μm. More than two spheroids may partake in a waltzing bound state, leading to linear *Volvox* clusters, as viewed from above in (d), where the scale is 500 μm.

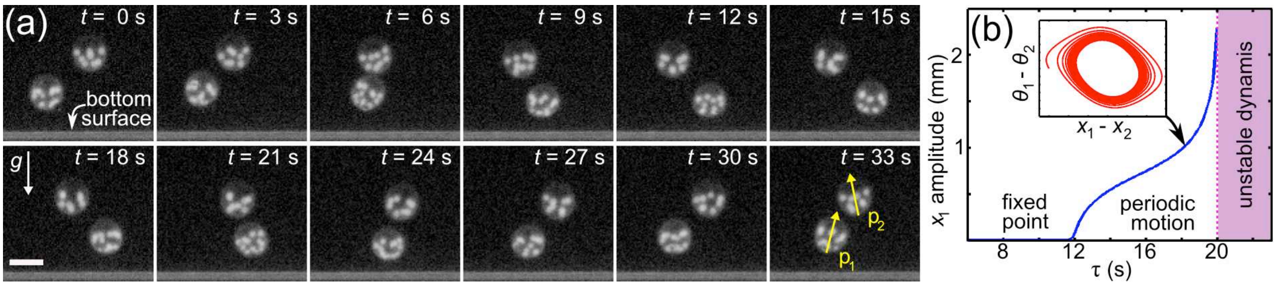

FIG. 2: (a) Side views of a pair of *V. carteri* spheroids as they perform the minuet dance. Scale is 600 μm. Yellow arrows indicate the anterior-posterior axes $\mathbf{p}_i$, at angles θ_i to the vertical, of the two spheroids. A simple dynamical system that allows only spheroid axis tilt θ_i and horizontal motion, with position coordinates x_i, of two mutually advected stokeslets is shown to lead to behaviour that accounts for experimental results. A phase portrait (b) of the oscillation amplitude in the x-direction is shown as a function of the bottom-heaviness time scale τ.

Tethered fleximags as artificial cilia

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Assemblies of cilia and isolated flagella are used by microorganisms to propel themselves in liquids. They play also a crucial role to generate nodal flow on embryos, determining the left-right asymmetry of organisms. At very low Reynolds numbers, propulsion or fluid pumping can only be achieved if the motion during a beating cycle is non reciprocal. In order to study the mechanisms involved in symmetry breaking and coordinated beating, we make artificial microscopic cilia from superparamagnetic colloids elastically linked by a polymer nanolayer. These "fleximags" can be actuated by a homogeneous, time-dependent magnetic field and share common features with real cilia: they have a very large aspect ratio, are highly flexible, move in three dimensions and are actuated through bending torques distributed along their full length. Their dynamics is essentially controled by a balance between viscous torques and the magnetic driving torque expressed as a dimensionless actuation frequency or Mason number: $Ma \propto (\eta \omega L^2 \mu_0)/B^2$ where η is the fluid viscosity, L the cilium length and B the magnetic field amplitude. This leads to an oscillation amplitude proportional to $Ma^{-1/2}$ (fig.1) both for symmetric and asymmetric beating.

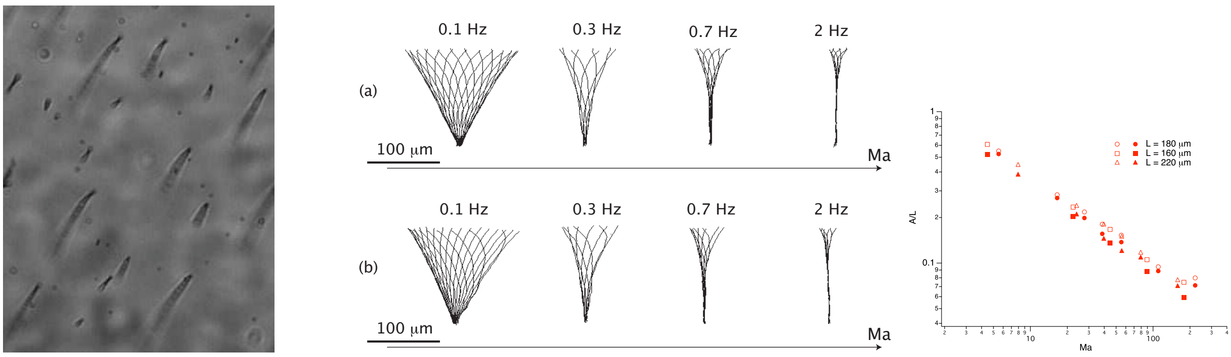

FIG. 1: Array of tethered fleximags (left, with C. Javaux, N. Coq & D. Bartolo). Shape of a single filament during a beating cycle, as a function of the Mason number for symmetric (a) and asymmetric (b) beating patterns. Normalized oscillation amplitude as a function of Mason number (right).

The dynamic behaviour can be analyzed in a continuum limit, considering the fleximags as inextensible magnetic filaments, with a bending elasticity . The shape of the filament is parametrized by the angle $\theta(s)$ between the filament tangent and a fixed direction. Writing the force and torque balance on each element of the filament, and using resistive force theory leads to two dynamical equations for the tension and θ. The numerical solutions of these equations provide a good description of the observed shapes (fig. 2). In addition, the flow induced by the filament motion is computed, taking into account the influence of the wall: a net (but small) pumping is observed for an asymmetric beating. These first observations open clearly the perspective for the study of 3D filament paths and the optimization of pumping efficiency.

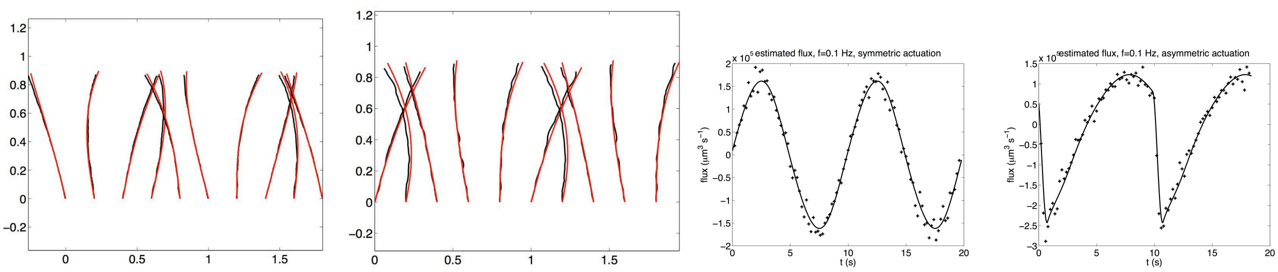

FIG. 2: Left : Measured shapes (black) compared to the prediction of the continuum model (red) for symmetric and asymmetric beating. Right : corresponding time dependence of the horizontal flow velocity.

Propulsion by surface distortion in complex fluids

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Fluid mechanics plays a crucial role in many cellular processes. One example is the external fluid mechanics of motile cells such as bacteria, spermatozoa, and essentially half of the microorganisms on earth. These organisms typically possess flagella, slender whiplike appendages which are actuated in a periodic fashion in a fluid environment, thereby giving rise to propulsion.

Many biologically-relevant situations in cell locomotion involve non Newtonian fluids. Important examples include the motion of spermatozoa in cervical mucus, or the movement of bacteria in biofilms. In this work, we present quantitative models of cell locomotion in polymeric solutions.

We use asymptotic methods to estimate the effect of viscoelastic stresses on the kinematics and energetics of locomotion and transport in complex fluids. We first derive integral equations which allow to calculate directly the swimming kinematics for a cell moving in a polymeric solution by using only the solution of the Newtonian swimming problem. The results are derived rigorously in the limit of small-amplitude swimming, but are valid for arbitrarily large values of the Deborah number - which is the relevant biological limit. We then illustrate how these results can be applied to real biological swimmers, such as ciliated microorganisms. Finally, we demonstrate explicitly how viscoelastic stresses can be exploited to design reciprocal swimmers, thereby confirming the breakdown of Purcell's scallop theorem in a polymeric fluid.

Flow induced flagellar synchronization in *Volvox carteri*

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The importance of fluid dynamics in biology is well illustrated by the fact that one of the most highly conserved structures among eukaryotes is the cilium. As cilia are responsible for tasks ranging from fluid transport in the respiratory system to breaking embryonic left-right symmetry, there is great importance to the question of how neighboring cilia synchronize, particularly in producing metachronal waves, in which long wavelength phase modulations travel along carpets of cilia. The multicellular green alga *Volvox carteri*, Fig.1, is well suited as a model to study flagellar interactions. Thousands of somatic cells are regularly embedded on the colony's periphery and beat their flagellar pairs to keep it at the correct height in the water column. Here we report for the first time that despite the absence of any kind of intercellular connections, flagella present a remarkable degree of synchronization across the colony, giving rise to large-scale metachronal waves. As a first step in understanding such coordination, we study the behavior of the two flagella of individual isolated somatic cells. Using a combination of microscopic high-speed imaging and micromanipulation, we show that the flagella's synchronization is greatly enhanced when the cell is immersed in a continuous external flow, similar to that experienced while part of a whole colony. We present experimental evidence that such flow has an effect on the behavior of each single flagellum, and propose a mechanism responsible for the observed enhancement of synchronization. Our results suggest a novel mechanism for the spontaneous emergence of large-scale flagellar synchronization.

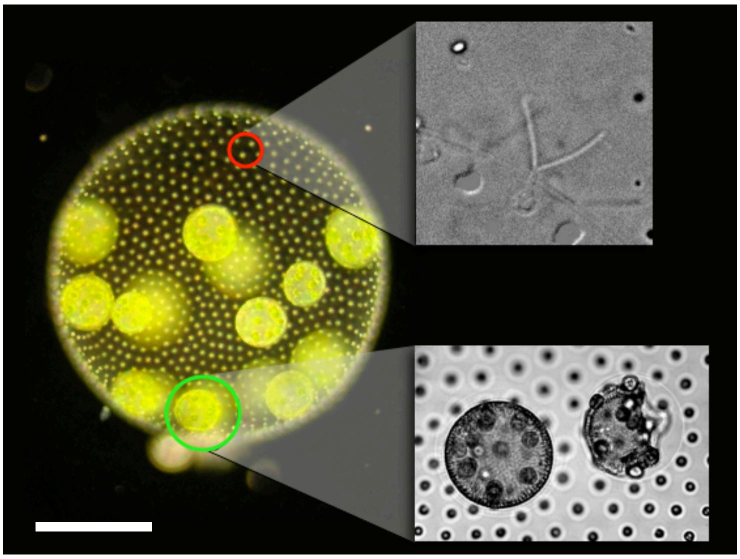

Figure 1: Thousands of small somatic cells keep *Volvox carteri* afloat while few very large germ cells prepare the next generation. Scale bar 100μm.

Collective locomotion of soft active particles

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Suspensions of micro-swimmers such as bacteria, or even man-made microrobots are encompassed in the wider class of active materials. These media generically include active particles which continuously dissipate energy supplied by internal or external actuators. Much effort are currently devoted to understanding the collective dynamics of self-propelled particles. We here investigate another class of active suspensions made of soft particles which can be actively deformed but which cannot propel themselves. Any soft active particle (SoAP) which experience time reversible deformations belongs to this class. At the micro-scale (at zero Reynold number) the so-called Purcell's scallop theorem prevents reciprocal active particles to swim, however we demonstrate explicitly that there is no many-scallop theorem [1], Figure 1. We show for instance that two SoAPs undergoing reciprocal deformations, can swim collectively; and, in general, experience effective long-range interactions. These results are first derived for a minimal dimers model and generalized to more complex geometries on the basis of symmetry and scaling arguments. We also explain how such cooperative locomotion can be realized experimentally by shaking a collection of soft particles with a homogeneous external eld. Eventually we extend these results to infinite chains of SoAPs hydrodynamically coupled. We attempt to reveal large scale cooperativity both for the dynamics of the conformational and translational degrees of freedom [2].

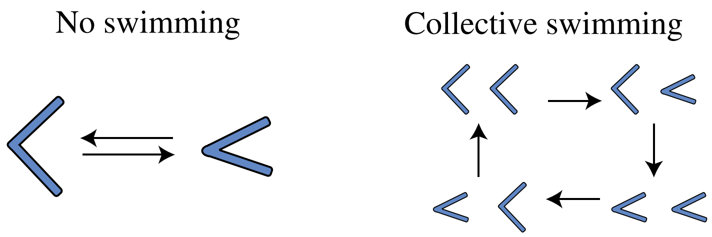

Figure 1: A body deforming its shape in a time reciprocal fashion cannot swim in average at small scale, i.e. at zero Reynold number (left). On the contrary two reciprocal particles interacting hydrodynamically can swim collectively if the glogal deformation sequence is not time reversible (right).

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Buckled in translation

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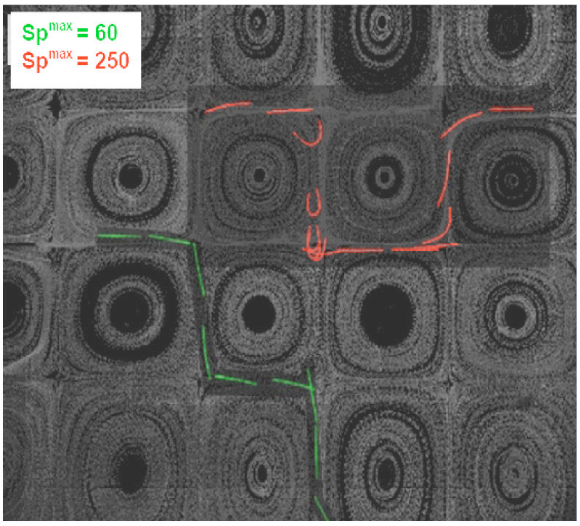

The fluid-structure interaction of an elastic fiber in a viscous flow can lead to the deformation of the fiber and thus, to a modification of its dynamics in the flow. Such interactions, highly non-linear, are widely studied numerically: in [1] the authors show that the buckling of filaments in a sheared fiber suspension is at the origin of anomalous rheological properties observed in these systems. In [2], Young and Shelley demonstrate that the buckling transition alters the translational diffusive motion of the filament. However, experimental observation of this "deformation - translation" coupling are still scarce and need to be further explored.

In this work, we study experimentally the transport and deformation of a macroscopic elastic fiber (Length ~ 10 mm, radius ~ 0.1 mm, Young modulus ~ 100 kPa) in a viscous periodical flow, namely a lattice of counter-rotating vortices, created by an electromagnetic forcing.
We show that the local elasto-viscous number Sp(x,y), which compares the relative intensity of viscous compression and elastic forces acting on the fiber, controls the buckling transition of the fiber in the lattice. We then compare the transport properties of rigid-like and deformable fibers. The deformation of a fiber increases its diffusivity in the lattice.

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[2] Young et. al. Phys. Rev. Lett. **99** (2007)

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Biomechanics

Microscale Instability and Mixing in Driven and Active Complex Fluids

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Complex fluids are fluids whose suspended microstructure feeds back and influences the macroscopic flow. A well-known example is a polymer suspension and a novel one is a bacterial bath wherein many swimming micro-organisms interact with each other through the surrounding fluid. In either case, these systems can display very rich dynamics even at system sizes where inertia is negligible, and both systems have important applications to micro-fluidic mixing and transport. They are also very difficult to model and understand, as the micro- and macro-scales are intimately coupled, and making progress can require approaches that span the particle and continuum scales. I will discuss two examples motivated by recent experimental observations. In the first, I discuss numerical studies using classical nonlinear PDE models of viscoelastic flow at low Reynolds number. Using the extensional flow geometry of a four-roll mill, we have found symmetry breaking instabilities that give rise to multiple frequencies of flow oscillation, the appearance of coherent structures, and fluid mixing driven by small-scale vortex creation and destruction. In the second example, I will discuss recent modeling and simulations of active suspensions made up of many swimming particles. We find that such systems can stable or unstable at large-scales, depending upon the micro-mechanical swimming mechanism, and if unstable the flows have coherent structures whose stretch-fold dynamics yields rapid mixing.

A model describing fish locomotion

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The purpose of this work is to describe the fish locomotion using a simple model. The fish body is approximated as a thin elastic media that interacts with a fluid at high Reynolds number. The fish muscles are included in the model as a spatially distributed and active torque, that permits the fish body movement. Within the slightly deformed approximation, we compute the stresses induced by the fluid over the fish body. Theses stresses are then included in the equations of motion that predicts the location of each part of the swimmer, and the swimming gait is then calculated. For each parameter set of the active torque, we compute the velocity, the power dissipated and its corresponding efficiency.

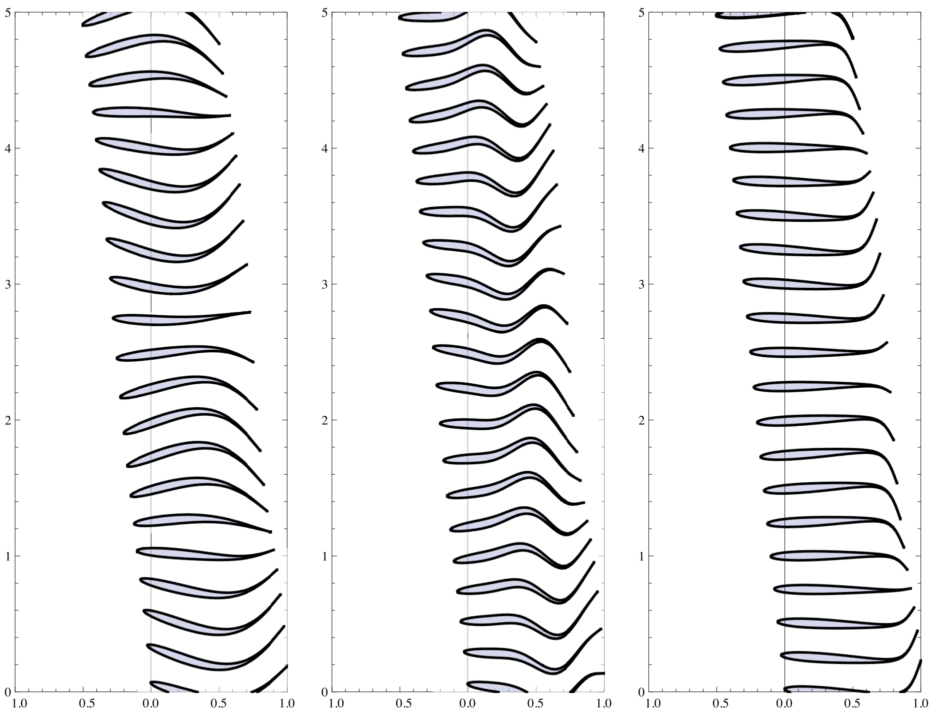

Figure1. Examples of swimming gaits.

Unbinding Dynamics of lipidic membrane near a substrate

by

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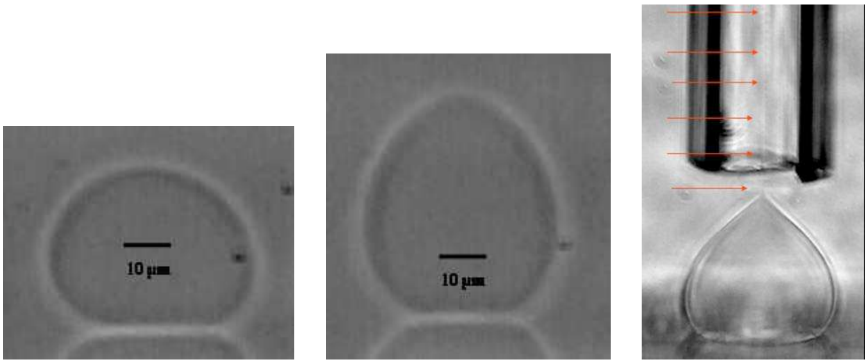

(a) (b) (c)

FIG. 1 – (a) A slightly deflated vesicle on a substrate before an application of hydrodynamic force. (b) The deformed vesicle after an applied hydrodynamic force. (c) Instability of lipidic tube during an unbinding of deflated vesicle by a high hydrodynamic force.

Closed lipidic membrane called vesicle is rested on a substrate by the interplay of adhesion energy, gravity and curvature energy at equilibrium. Various forms of vesicles ranging from inflated until deflated ones are observed. The inflated vesicle whose form is a truncated sphere occupies less contact area compared to the deflated one. The experimental setup allows to apply an axisymetric hydrodynamic force and to observe its shape and the thickness of the water film between the membrane and the substrate during the process of unbinding (fig. 1 a. and b.) Two regimes of unbinding dynamics are found depending on the reduced volume (a measurement of vesicle deflation). The first regime of inflated vesicle corresponds to the thickening of water film for the constant contact area. The second regime of deflated vesicle involves the strong reduction of contact area at constant water film thickness. When the extremely deflated vesicle occupying a large contact area is unbinded by a strong hydrodynamic force, a lipidic tube (fig. 1 c.) is created.

High-Fidelity Computational Studies of Canonical Problems in Biomorphic Locomotion

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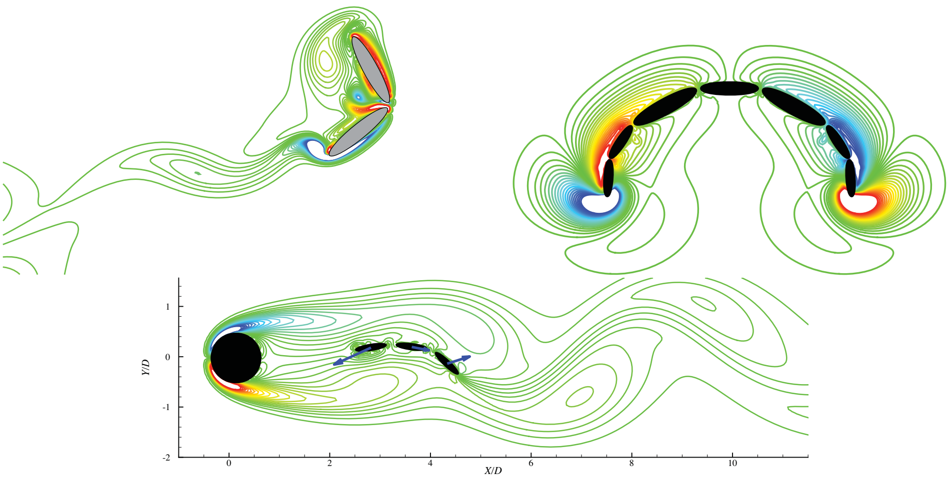
Locomotion mechanics at moderate Reynolds number (10^1 - 10^5), as evident in creatures such as insects and fish, are fundamentally based on the reaction force supplied by the fluid against an accelerating flexible surface. Flexibility is intrinsic to almost all biological surfaces, though its role in this locomotion regime is still poorly understood. In particular, it is unclear to what extent a swimming or flying creature controls the shape of its fins/wings/tail ('active flexibility') or allows these surfaces to be deformed by the fluid ('passive flexibility'). Undoubtedly, there is some degree of mixing between these types of flexion, which likely provides benefits in agility and energy savings when 'optimized'. It is also well accepted that the vorticity that is generated and shed by the deforming surface as it sweeps through the fluid plays a central role. These two features – elastic deformation, and vorticity production and transport – are strongly coupled in locomotion. Furthermore, their interaction does not readily admit description with low-order mathematical models.

In this work, we identify and explore a number of 'canonical problems' that represent abstracted features of biomorphic locomotion. These problems are analyzed with high-fidelity numerical simulation: the full viscous fluid and body dynamical equations are solved. This approach is designed to proceed slowly through a hierarchy of such problems, in which complexity is gradually introduced. In this fashion, we can develop the simulation and analysis tools necessary to obtain a better understanding of locomotion with flexible surfaces. Our simulations are based on the viscous vortex particle method. The method couples the fluid and body dynamics by simultaneously evolving the deforming surface and fluxing new vorticity into the fluid.

The first canonical problem consists of a flapping wing with two rigid components connected by a torsion spring (left, top of figure). This problem is explored with both simulation and experiment, which serves as a useful validation exercise. The stiffness of the wing and the flapping kinematics are varied for optimizing the lift and efficiency of the system. The second problem involves the free swimming of an articulated jellyfish model (right, top of figure). In this problem, we show that the efficiency of swimming can be improved considerably over a fully active swimmer by designating some hinges as flexible and appropriately selecting their stiffness. In the third problem, we explore the mechanics of a completely passive three-link system in the wake behind a cylinder (bottom of figure). We demonstrate that passing vortices induce undulations in the system, but that flexibility is not necessary for the system to propagate forward. Finally, we will discuss extensions of the models to full elastic structures and three-dimensional problems.



Experimental studies on model flapping-wings

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Flapping motion is the basis of locomotion in insects, birds, and fish. For insects and birds the flapping motion not only generates the thrust force but also the lift force that allow them to fly. These propulsive and manoeuvring forces are produced owing to the interaction between flapping wings and fins and their surrounding fluids. Although many studies on actual flapping extremities have been motivated looking forward to a better understanding of this form of propulsion, a wide set of open questions remain especially concerning the ultimate goal of using flapping wings as a means of producing propulsive and manoeuvring forces in man-made devices. From a practical point of view, simple but important basic questions such as, for instance, the optimal flapping frequency and amplitude that should be used to drive forward flapping flight are still looking for a definitive answer. The problem being particularly complex when the flapping appendage is not rigid but flexible so that its elastic properties become part of the control parameters.

A series of key dynamical elements, such as the creation and organization of vorticity, can be often studied using a quasi-2D picture of the velocity field in a well chosen plane and exploiting some symmetry hypothesis. We have recently used a simple pitching foil experiment in a hydrodynamic tunnel to study different aspects of the reverse Bénard-von Kármán vortex street that is often associated to flapping-based propulsion. This has permitted to identify the transitions between different dynamical regimes in the wake of the foil, shedding some light upon the mechanisms that could delimit the practical ranges in the parameter space of a flapping system (see figure below).

Currently ongoing work on the effect of wing flexibility in the transitions observed in the wake of the flapping foil will be presented at the conference.

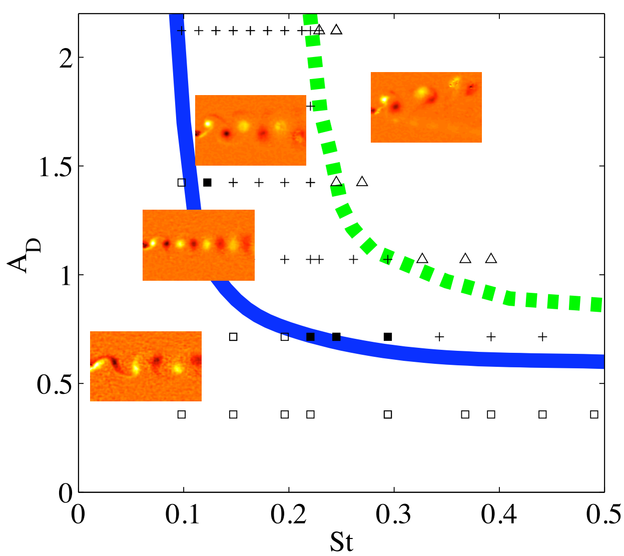

Figure: Transitions in the wake of a flapping foil in the frequency (St) vs. amplitude (A_D) parameter space [From Godoy-Diana, et al. 2009 (to appear in J. Fluid Mech.)]. Solid line: transition between Bénard-von Kármán (BvK) and reverse BvK wakes. Dashed line: symmetry breaking of the reverse BvK wake. Typical vorticity fields are shown as inserts on each region.

Eel-like body swimming : extension of the elongated body theory of Lighthill, RANSE simulations and optimisation

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Fishes have always fascinated human beings with their incredible ease to couple instinctively Newton's laws and Navier-Stokes equations in order to swim. The efficiency and the great maneuvrability of their locomotion function compose a tremendous application field for fluid engineering illustrated by the growing number of related biomimetic studies. Among them, a French project (ROBEA followed by an ANR project RAAMO since last year) aims at designing an efficient autonomous flexible underwater eel-like robot. In this framework, researches related to the scope "eel-like body swimming" have been carried out.

On one hand, the control of such a robot needs an accurate model of fluid forces acting on the body. To fulfill this requirement, a simplified model has been designed to have a real time simulator. It is based on the Lighthill's original "Elongated Body Theory", but extended in several ways : (i) Lighthill only investigates planar swimming in straigth line with an imposed constant forward velocity, while in our model, a quite complete set of gaits (including turning, starting, rising,...) can be considered, (ii) the internal dynamics of the beam-like fish are also solved in order to compute the torque control law, (iii) the swimming dynamics are self-propelled and thus the external dynamics of overall rigid motions are solved rather than being imposed, (iv) the pure reactive model of the Lighthill theory is completed with a resistive model to take into account longitudinal and transversal viscous effects. The last point is crucial to adress self-propulsion, because if no dissipative forces can counterbalance the inertial propulsive ones, the fish perpetually accelerates.

On the other hand, the RANSE (Reynolds Averaged Navier-Stokes Equations) code, named ISIS-CFD, developed by the CFD group of the Fluid Mechanics Laboratory of ECN has been extended to couple the RANS equations with the Newton's law of such a body (i.e. a deformable body with an imposed deformation). After studying the grid convergence and the influence of the turbulence model, self-propulsion simulations have been used as reference database. Once the calibration step of viscous corrections achieved (with simple gaits: initial forward speed in a rigid configuration...), the coefficients of the simplified model were fixed definitely. For the moment, only planar deformation (but with 3-D domain) have been compared, but 3-D deformation are in progress. Numerous cases of validations (forward and turning gaits) have shown very good agreement between this simplified model and reference results provided by the Navier-Stokes solver : differences do not exceed 5 %, except one (10 %) with a particularly slow forward velocity. For example, fig. 1 shows the comparison of the solved head trajectory for an imposed deformation of the body leading to a turning manoeuvre.

Considering its high reduced CPU time consumption, the simplified model is not only suited for the on-line command of eel-like robot, but also for optimization purpose. By-passing the RANSE solver with the simplified model, some optimization techniques (simplex and genetic algorithms available inside ISIS-CFD) have been applied to improve parameters of the curvature of the body backbone imposed in time. First attempts trying to optimize velocity always lead to the boundary of the design parameters. On the contrary, with efficiency as cost function, optimization reaches values in the definition domain of parameters. Validations of the optimized law with a RANSE simulation (fig. 2) show the same trends concerning the cost function. Until now, only the fluid point of view has been considered. We plan to add the internal dynamics of the body inside the optimization process to improve the global efficiency of the robot.

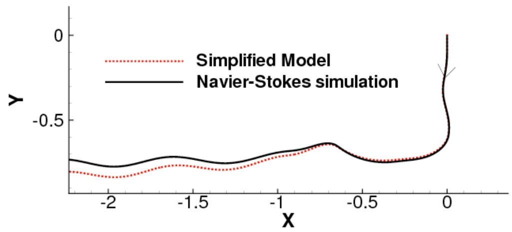

Figure 1: Trajectory for a turning gait

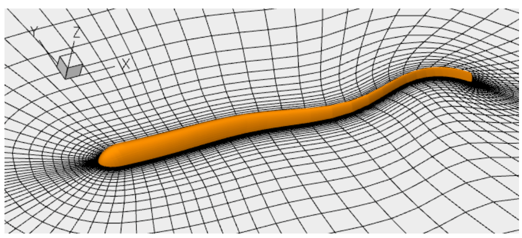

Figure 2: RANSE simulation with the optimised law

Study of the ultrafast trap of an aquatic carnivorous plant

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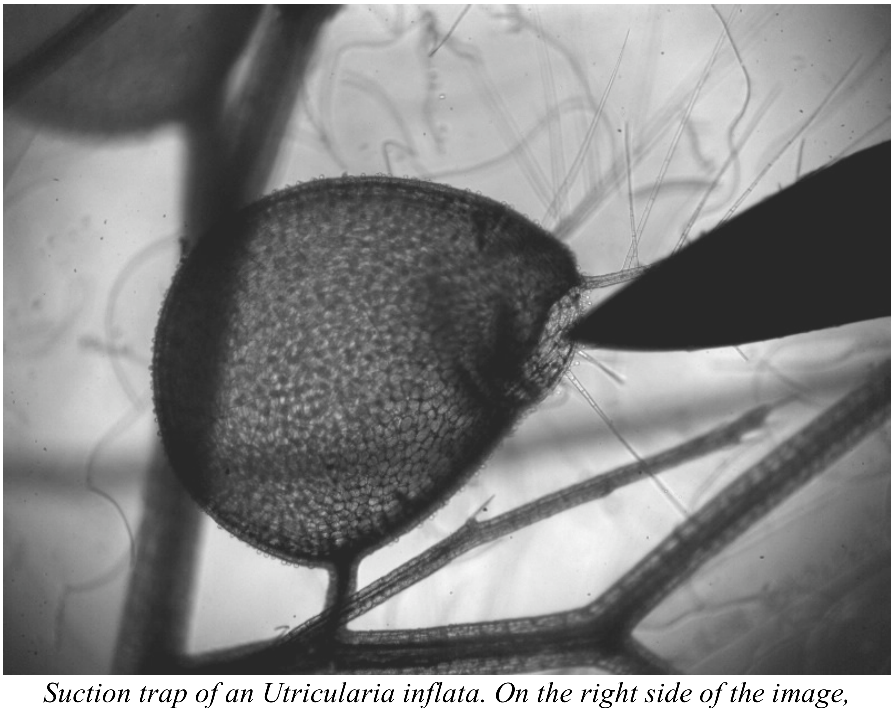
A process difficult to perform within the channels of a Lab on a chip is the sudden transfer of a small sample of fluid in a closed container. This operation is naturally found in the vegetal kingdom when considering the aquatic carnivorous plants Utricularia (common name bladderwort). This plants are gifted with suction traps: a contact opens a door, the trap sucks in liquid, and then the door closes hermetically, all this sequence within the impressive time of a few milliseconds (Skotheim 2005), barely visible with the naked eye.

We present an on-going experimental study. The motion of the trap door is recorded by a high-speed camera. Attention is focused on succession of the two distinct phases of the suction : first the door opening and then the door closure. The motion is therefore different from the close only traps of the Venus flytrap (Forterre 2005). We also record the associated fluid motion.

The aim of this study is to present a model for the trap that will couple the elastic properties of the plant walls with the fluid flow. A model will prove useful for the design of a biomimetic reproduction of the trap, and its implementation in a microfluidic circuit.



Suction trap of an Utricularia inflata. On the right side of the image, the needle tip is pointing to the door (500 micrometer large).

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Biomechanics of fern spores discharge

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1 Abstract

We study the mechanism of spore discharge in ferns. It consists in the fast released of a spring-like structure, the sporangium, which contain the spores, after its opening due to dehydratation. Thirteen cells constituting the annulus surround the capsule containing the spores (about 300 microns in diameter). Through a thin membrane, the water inside these cells evaporates. The resulting decrease in volume along with cohesive forces induced lead to a change in curvature of the annulus. We analyze this opening phase for natural, isolated sporangia and we compare our results with a simple theoretical model. For the first time, we observe, using high speed imaging, the fast closure motion of the sporangia by releasing the elastic energy stored, that leads to the spores ejection at a speed around 10 m/s. We find, in particular, that the motion presents two steps, an uncommon behavior among fast plant motion which enable a very efficient discharge: a wonderful example of an autonomous catapult.

Motion of a capsule in a simple shear flow: Coupling of finite element and boundary integral methods

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Bioartificial capsules consisting of an internal liquid protected by a thin hyperelastic wall have many practical uses for pharmaceutical, cosmetic or bioengineering applications. When suspended in another flowing liquid, capsules undergo large deformations because there are strong fluid-structure viscous coupling effects due to the low-Reynolds-number flows of the internal and suspending liquids. It is known from previous experimental and numerical studies that the mechanical behaviour of the capsule wall is dominated by in-plane membrane tensions. However, compressive tensions can occur locally and create wrinkles that depend on the bending stiffness of the interface. The bending of closed shells is a difficult modelling problem for which an appropriate method is based on finite element (FEM) representations of the wall.

The objective of this work is to show how a a finite element model of the capsule wall can be coupled with a boundary-integral formulation of the Stokes flow equations. As a first step, we describe the capsule wall by means of a membrane model (without bending stiffness) and consider a hyperelastic constitutive law that accounts for large membrane deformations.

The fluid-structure coupling leads to a non conventional implementation of the finite element model. Indeed, at a given time step, the flow imposes displacement increments to the wall. The hyperelastic constitutive law yields the elastic tensions in the membrane. The load on the capsule wall is then given by the solution of the weak form of the equilibrium equations obtained from the virtual work principle. This approach differs from the methods commonly used in classical capsule studies, which impose *local* equilibrium between the wall elastic forces and the viscous load.

The membrane is meshed using triangular elements, with an isoparametric interpolation of the displacements and external load. Both linear (P_1) and quadratic (P_2) interpolation methods are tried. At each time step the FEM yields the load on the membrane as explained above. The Stokes equations are then solved on the same mesh using a boundary integral method (BIM), that computes the velocity at the nodes from the distributed load on the membrane. At the following time step, the position of the nodes is updated through Lagrangian tracking by means of a second-order Runge-Kutta integration and the process is repeated.

We focus on the case of an initially-spherical capsule enclosed by a neo-Hookean membrane and suspended in a simple shear flow. The results found are consistent with previous studies [1,2]. In particular, for moderate flow strengths, a stable equilibrium shape is attained, without compressive tensions anywhere in the membrane. The deformation of the capsule is then identical to the one computed by Lac et al. For small flow strengths, compressive tensions appear on some parts of the membrane and make the equilibrium state unstable. Such compressive tensions lead to numerical instabilities in local equilibrium membrane models. With FEM, the equilibrium shape we obtain exhibits numerical wrinkles, but remains stable because the FEM introduces some numerical bending stiffness to the membrane. The same conclusion is reached independently of the interpolation method used.

In conclusion, coupling FEM and BIM leads to accurate capsule deformation modelling. It allows to sustain some compressive tensions in the wall even though the mechanical wall model does not account for bending stiffness. This is a very convenient feature when the bending effects remain localised and weak. Nevertheless, the results obtained in those cases do not model exactly the physical behaviour of the capsule wall: its bending stiffness needs to be taken into account through the use of a shell model. The method we presented must then be extended to include bending effects.

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Compliant walls

Hairfoils: passive actuators for flow control

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A passive procedure of separation control inspired by the dynamics of dorsal coverts on the wings of birds is studied numerically. The model of the feathers has been developed in previous work which focussed on the properties of self-adaptation of a porous, anisotropic and compliant coating placed on a circular cylinder. Results show that the flow-induced vibrations of feather-like control elements during gliding flight can enhance aerodynamics performances of birds. This passive flow manipulation technique yields drag reduction, associated to lift enhancement, related to the effect of the feathers/actuators on the near-wake of the body for flight values of physical relevance. The mechanism allows birds to reduce significantly the power consumed to fly, without any activation cost, since feathers self-adapt to the flow. The results support the idea that upper wing coverts in birds do not play simply a thermal insulating role; a technique of separation control inspired by the behaviour of coverts can be envisaged to reduce pressure drag and improve locomotion efficiency of road, aerial and aquatic vehicles.

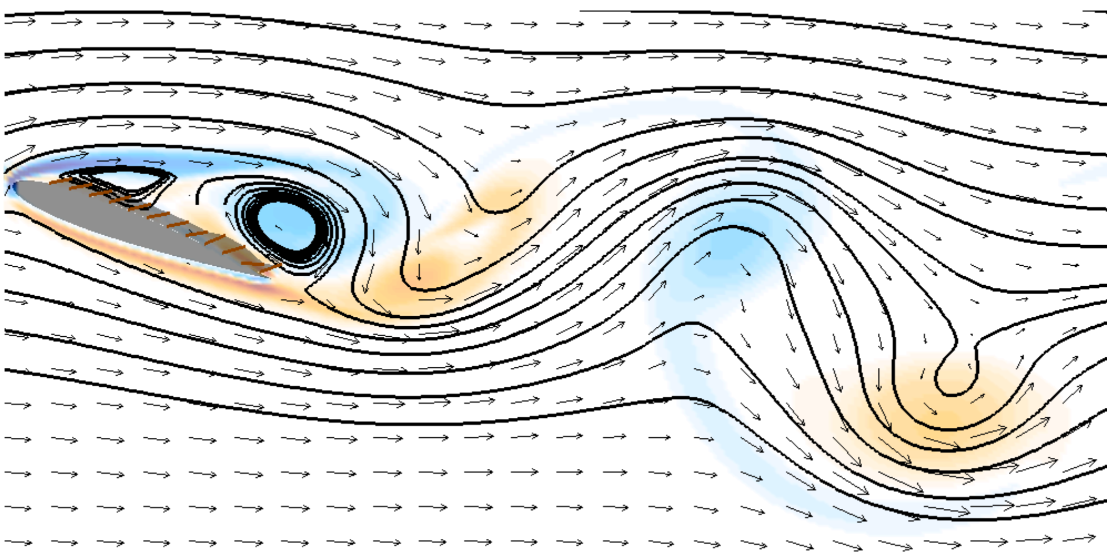

Figure 1. Fluid velocity vectors and streamlines around the airfoil, superimposed on contours of vorticity. The model of dorsal coverts is schematically shown by the grey layer, and the twelve reference cilia of the layer are displayed in brown.

The fluid–solid boundary condition for uniform flow over a compliant surface

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When modelling fluid flow over a compliant surface, a common simplification is to consider the fluid flow to be uniform [1–4]. In this case, no flow through the surface implies the linearized boundary condition (BC) is continuity of normal particle displacement between the fluid and the surface; this is sometimes referred to as the Myers BC [5]. However, Aurégan *et al.* [6] have shown using a low-velocity limit that a viscous boundary layer modifies this behaviour. In the high-frequency limit they found the Myers BC is retained, but in the low-frequency limit they found continuity of normal mass flux to be the correct BC.

In this talk we analyse this further using a combination of numerics and asymptotics. Analytic progress will be presented in the high- and low-frequency limits without resorting to the low-velocity limit, using a Multiple Scales approach in the high-frequency limit. This enables analysis of any critical layers, where the phase-speed of disturbances is equal to a velocity in the boundary layer, and these are shown to lead to caustics in the Multiple Scales analysis. Considering a harmonic dependence $\exp\{\mathrm{i}\omega t - \mathrm{i}kx\}$, the compliant surface may be described by its impedance $Z = p/v$, where p is the pressure on the surface and v is the surface's velocity. Due to the boundary layer, the fluid in the uniform flow may be thought of a seeing a boundary satisfying the Myers BC with an effective impedance Z_{eff}. Figure 1 plots numerically-calculated Z_{eff}/Z for varying k, for air with a Blasius boundary layer at a high frequency. It can be seen that $Z_{\mathrm{eff}}/Z \approx 1$ over most of the k-plane, verifying [6] in the high-frequency limit. However, poles and zeros are also present, as well as a branch cut. The branch cut, which originates from a point with phase speed equal to the uniform flow speed, will be explained mathematically. Time permitting, this talk also aims to mention the effect of the boundary layer on stability analyses, and to investigate any differences when the fluid is incompressible.

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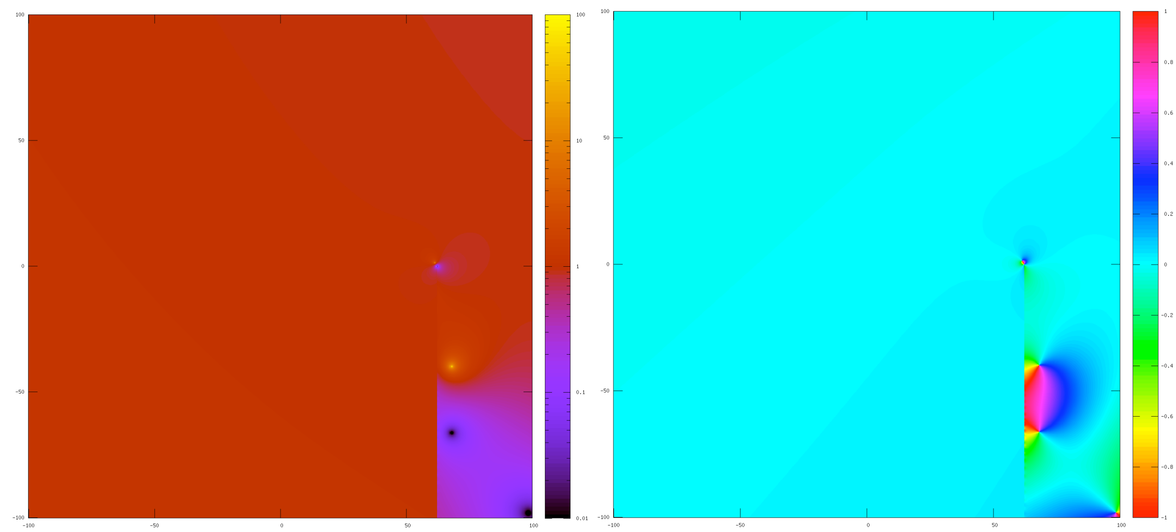

Figure 1: The modulus (left) and argument (right) of Z_{eff}/Z in the k-plane. Nondimensionalized by the speed of sound and the distance downstream of the leading edge, the Mach number $M = 0.5$, frequency $\omega = 31$, Prantl number $\mathrm{Pr} = 0.7$, and ratio of specific heats $\gamma = 1.4$.

Near wall turbulence control via flexible micro-hairs

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Extended Abstract: In our previous studies flexible micro-hairs made from elastomers were used as sensory hairs for wall shear stress imaging, see Brücker et al. 2005, 2007. As sensory hairs, they have a length in the scale of the viscous sublayer with a typically ten-times smaller diameter and a large spacing such that they do not influence or alter the boundary layer flow itself. The balance of drag and elastic restoring forces of the structures is used as a simple sensory principle with the micro-pillar tip displacement being proportional to the local wall shear. Based on recent discussion about the effect of hairy surfaces on transition and flow separation (see Bottaro, "Hairfoils: passive actuators for flow control"), we focus in the recent experiments on the effect of elastic micro-hairs in a dense spacing on transition and bursting events in a two-dimensional turbulent boundary layer.

The hair foil used in our study consists of a dense array of flexible micro-pillars (diameter 100μm, length 1000-2000μm which is 10-20 viscous wall units, spacing of 500μm) with uniform circular cross-section representing homogeneous circular beams with a planar base and tip, see Fig. 1. The foil with a size of 5×5cm^2 is positioned at the surface of a flat plate (total length of 3 meter) in a low-turbulence oil flow channel which was designed for high-resolution optical measurements. A tripping wire (diameter 1.5*mm*) was fixed on the plate 0.15*m* downstream of the trailing edge to trigger a transition scenario based on the evolution of Tollmien-Schlichting waves (TS). The pillars are made of a transparent elastomer (PDMS, Poly-Dimethylsiloxane) with a relative low Young's modulus of $E = 1.6 \cdot 10^6 N/m^2$. A digital high-speed camera (Photron APX-RS, recording rate 3000 fps) equipped with a telecentric lens system (M=3) was used to record the hair orientation and motion. In addition, several smaller micro-pillar sensory hairs are located downstream of the hair foil in order to measure the effect on the mean and fluctuating part of the wall-shear. Standard image processing routines were used to measure the pillar tip displacement with high resolution.

The preliminary results already show the advantage of the structures elasticity in the viscous-elastic fluid-structure coupling and its damping influence on the near-wall events of turbulent boundary layer flow. In addition, the flexibility of the structures allows for self-adaptation of flow control with Reynolds-Number and flow direction because of drag-forced bending and orientation of the micro-hairs. With increasing mean flow velocity, i.e. Reynolds-number, the micro-hairs bend more into streamwise direction and line-up each-other with the streamwise direction in form of thin strings oriented in streamwise direction. Those strings have already been discussed by Bartenwerfer & Bechert (1991) for possible drag reduction. They found that the thickening of the viscous sublayer is much larger than the effect of riblets. For the latter, drag reduction has been shown experimentally.

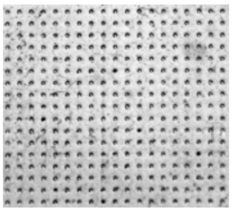
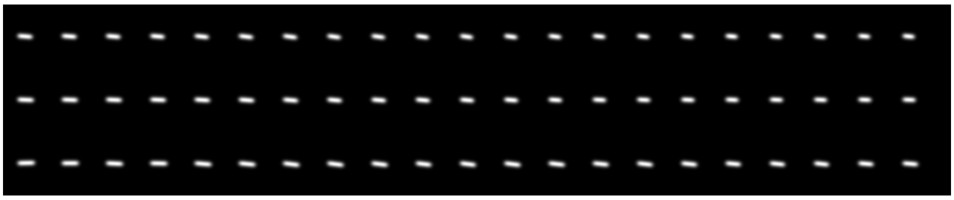

Fig 1: Left: image of hair foil with flexible micro-pillars; right: subimage of a 3×20 micro-hair segment at transitional flow

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Transient mechanisms in fluid systems with elasticity

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The fundamental question of hydrodynamic stability is: "Are there perturbations that can grow?", and this question is best answered by optimization. If the perturbation growing the most does not grow much, then, the flow can be safely qualified as "insensitive", otherwise it is sensitive, which is a good sign that something "special" is taking place.

Energy transfer is a possible feature in systems that have more than one energy reservoirs, such as those allowed by kinetic and potential energy. This is the case for elastic fluids and coupled systems, like those involving fluids and flexible structures.

In this presentation, we will analyse the response of the Poiseuille channel flow with compliant walls to external perturbations. We observe several mechanisms for energy growth, related to either waves traveling along the elastic walls, or through interactions of the walls with the main shear. Simple scenarii are investigated, leading to models that quantitatively reproduce the computed results. These results open a small window of understanding on the general question of transient growth mechanisms in fluid/structure systems.

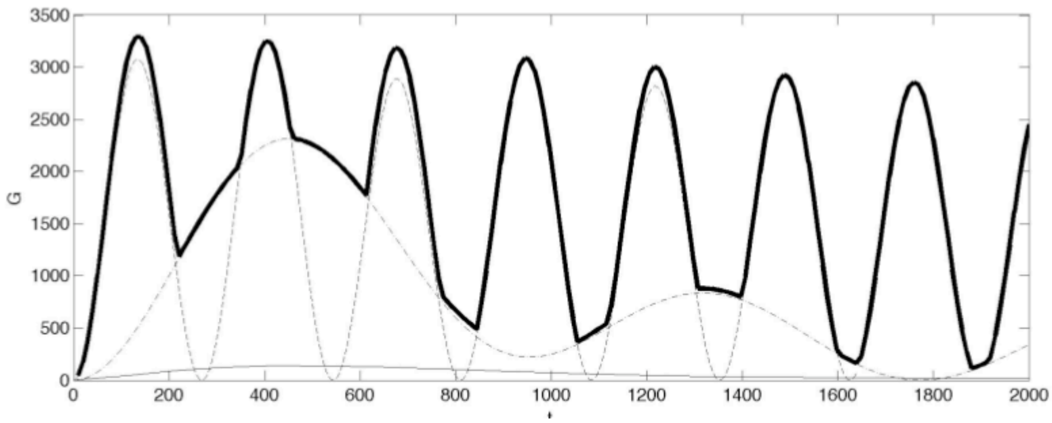

Figure 1. Envelope of maximum possible growth from an initial condition: there are clearly two different mechanisms active.

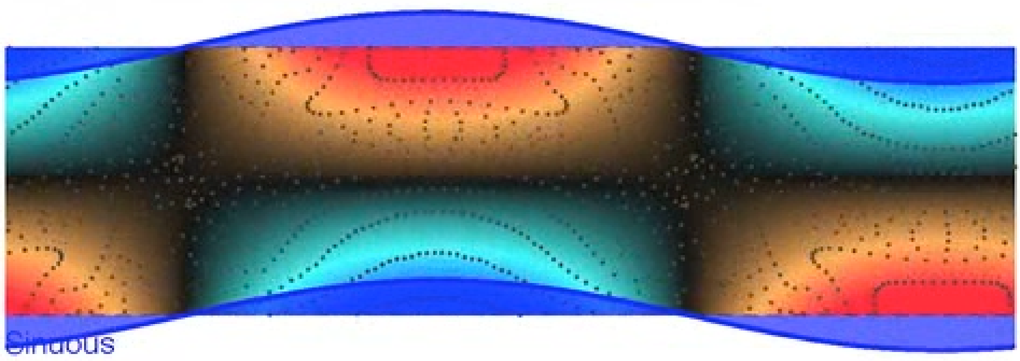

Figure 2. Snapshot of the evolution of the most growing initial condition, with sinuous symmetry. The colormap indicate the cross-plane velocity perturbation.

EIGEN-ANALYSIS OF FLUID-LOADED COMPLIANT PANELS

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In this paper we present and deploy a hybrid of computational and theoretical techniques to study the stability of a fluid-structure system that comprises flow over a flexible wall of finite streamwise extent. The system is two-dimensional but the methods developed may readily be extended to three dimensions. Of particular novelty in the present work is the ability of our methods to extract a full set of fluid-structure eigenmodes for systems that have strong spatial inhomogeneity in the structure of the flexible wall.

We first present the approach and some results of our recent work [1] in which a uniform flow interacts with a flexible plate held at both its ends. This configuration has a long history of investigation, for example see [2-6], using the Galerkin method. It is known to lose its stability to divergence at a critical flow speed. At higher flow speeds, the system recovers from divergence but modal-coalescence flutter sets in soon thereafter. In our modelling approach, we use the boundary-element method - see [7] for details - to determine the perturbations in the flow field due to wall motion. The pressure perturbations are used to drive the wall equation written in finite-difference form. This formulation allows the system to be expressed as a single matrix equation for the fluid-structure interfacial variable. This is then couched in state-space form and standard methods used to extract the system eigenvalues. Our results first vindicate the more economical use of the Galerkin methods for the case of a simply restrained homogeneous plate. Our investigation of inhomogeneous flexible plates reveal that spatial variation of the flexural rigidity (about the mean value of the homogeneous case) can be either stabilising or destabilisng for divergence. We also show that adding a further restraint within the streamwise extent of a homogeneous panel can trigger an additional, pre-divergence, instability that takes the form of single-mode flutter. The identity of the flutter mode is dependent upon the location of the added restraint. The mechanism for the fluid-to-structure energy transfer that underpins this instability can be explained in terms of the pressure-signal phase relative to that of the wall motion and the effect on this relationship of the added wall restraint.

Next we show how the approach developed above is extended to include boundary-layer effects. We loosely follow the general approach of [8] who directly extracted the eigenmodes for fluid-based instabilities in laminar boundary-layer flow over a rigid wall. In our work, the flow field is modelled by the continuity equation and the linearised perturbation momentum equation written in velocity-velocity form; this formulation is akin to that of [9]. The flow field is spatially discretised into rectangular elements on an Eulerian grid. The vorticity contained within each rectangular element is approximated by a zero-order vortex sheet element. A vector of flow-field element strengths is related to the values of a distributed vorticity field at control points through a matrix of influence coefficients. Like the potential-flow case, boundary-elements are used to enforce no-flux on the fluid-structure interface while the no-slip boundary condition is enforced through the injection of slip-velocity at the wall. Wall-singularity strengths are determined by enforcing the no-flux boundary condition at the wall that is influenced by both the motion of the wall and the flow elements. Similarly, enforcement of the no-slip condition combines the effects of wall boundary elements and the vortex elements within the flow field. This simultaneously determines all of the element strengths and thus the entire flow field is defined. The perturbation pressure is found through the Lighthill mechanism that relates streamwise pressure gradient and the injected flux of vorticity. The entire flow-structure system is assembled as a linear system for a single set of unknowns - the flow-field vorticity and the wall node displacements - that admits the extraction of eigenvalues. In doing so, the governing equations for the fluid are discretised using finite-differences for streamwise change while Chebyshev differentiation matrices are used in the wall-normal direction; this mixed approach is very effective for the high elemental aspect ratio appropriate to modelling boundary-layer dynamics. We then show how stability diagrams for the fully-coupled finite flow-structure system can be assembled, in doing so, identifying classes of wall-based or fluid-based and spatio-temporal wave behaviour in the system.

In summary, this paper serves to present a new and versatile approach to the modelling of the fluid-structure interaction (FSI) of a finite flexible wall. The method lies between classical hydrodynamic-stability theory and direct numerical simulation and enjoys a combination of the benefits of both of these hitherto distinct approaches to FSI problems.

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Fluid-Elastic interaction of spinning functionally graded thin-walled pipes conveying high temperature flow

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Spinning pipes that conveying fluid are of considerable interest and widely used in many fields. They have applications in the design of oil drill pipes, petrochemical equipments, drilling tools and such. Due to the thermal fluid-elastic interactions especially at high flow speed, rotating pipes are subjected to high fluid-thermal loads which can cause instability behavior during operation. For example, plugging in drilling equipment is one of the most common hydrodynamic problems during drilling operations. Functionally graded materials (FGMs) for high temperature structural applications are special microscopically inhomogeneous composite, whose thermo-mechanical properties vary smoothly and continuously in predetermined directions throughout the body of the structure. To the best of the authors' knowledge, in spite of its evident practical importance, no research work related to the modeling and fluid-elastic behavior of spinning FGM thin-walled pipes working under a fluid flow pressure as well as high-temperature environment has been done yet. Hence, the research work in this paper is devoted to this topic.

In this study a spinning functionally graded thin-walled pipes conveying high temperature flow under fluid-elastic loading is investigated. The governing equations, which are based on first-order shear deformation theory, include the secondary warping, temperature gradient through the wall thickness of the pipe and also the spinning speed. Moreover, quasi-steady flow pressure loadings and steady surface temperature are considered. Then, the pipe partial differential equations are transformed into a set of ordinary differential equations using the extended Galerkin method. Finally, having solved the resulting structural-fluid-thermal eigenvalue system of equations, the effects of fluid speed and geometric parameters on natural frequencies are presented. As well, the numerical results are compared with published results and good agreement is observed. Numerical simulations indicate the significant effects of the spinning speed , axial force and the temperature change through the thickness of the pipe. Furthermore, the instability boundary is obtained through eigenvalue approach.

Keywords: Fluid-Elasticity; Functionally graded materials; Spinning pipes; Internal flow; High temperature field

Vortex-induced flapping and twisting of a compliant plate

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Introduction: Flying animals (i.e. bats, insects, and birds) are characterized by compliant flight structures. For example, the skeletal frame of the bat's wings is composed of slender bones that deflect appreciably while the animal is in flight. In addition, the wings are often at high angles of attack where unsteady vortex shedding is important. To understand the interaction between compliance and unsteady flow structures, we examine a simplified physical model problem: the aeroelastic behavior of a cantilevered, low-aspect-ratio, flat plate (Fig. 1). The model has sharp leading and trailing edges and is able to twist and flap at frequencies determined by the elastic properties of the supporting member and the mass distribution of the plate.

Preliminary Results: Preliminary measurements consist of time-resolved hotwire velocity data in the near wake of the leading edge and optical measurements of the motion of the plate. Two types of transitions in the fluid-structure behavior are observed from these data: (1) a shift from small (subcritical) to large (supercritical) amplitude structural vibrations, and (2) an angle of attack dependent change in the subcritical vortex shedding behavior from well-defined, discrete vortices to the disorganized shedding of smaller scale flow structures. Waterfall plots (Fig. 2) showing the nondimensional frequency versus the normalized wind speed are assembled from wake velocity power spectra at specific values of reduced velocity, $U/(f_n c)$ (where f_n is equal to the resonant torsional frequency of the plate and c is the chord). The dominant frequency of each power spectrum is indicated by a circle or triangle marker. The red curve indicates where the vortex shedding frequency, f_v, equals the natural torsional frequency of the plate, $f_v = f_n$. At the lower angles, $\alpha = 30, 34°$ (Fig. 2a), the vortex shedding frequency scales linearly with velocity, consistent with bluff body shedding, and remains below the structural frequency (subcritical regime) for conditions tested thus far. As the angle of attack is increased to $\alpha = 38°$, the subcritical wake behavior changes significantly from vortex shedding at well-defined dominant frequencies at lower angles of attack to shedding occurring over a wider range of frequencies (although the maximum power remains close to $St = 0.2$). After the onset of flutter (supercritical regime), the vortex shedding transitions to more organized shedding at a frequency locked-in to the structural motion. This onset of flutter depends on resonance between the vortex shedding and the structural frequencies, thus the difference in the subcritical vortex shedding accounts for the absence of large amplitude fluctuations for the lower angle cases ($\alpha = 30, 34°$) where $f_v < f_n$ for the entire range of wind speeds tested. For the highest angle case ($\alpha = 38°$) the subcritical shedding frequencies are near the natural frequency for the same range of speeds and flutter is initiated at an approximate reduced velocity of 3. Therefore the critical flutter speed, i.e. the boundary between sub- and super-critical behavior, as a function of angle of attack undergoes a sharp transition due to this change in shedding behavior. The full paper will continue this investigation with a more detailed description of the compliant plate system, including particle image velocimetry (PIV) and force measurements characterizing wake structures and aerodynamic force production.

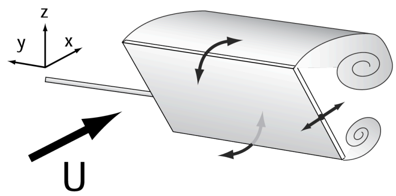
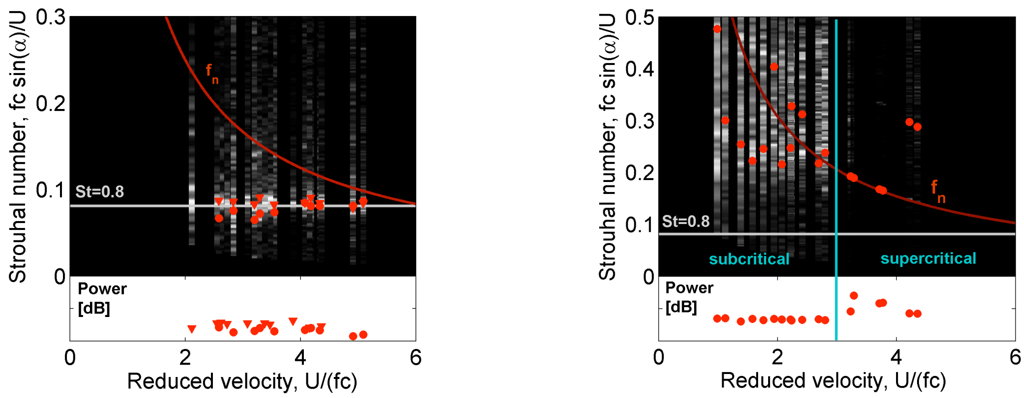


Figure 1: Compliant plate model



(a) Angle of attack = 30 and 34 degrees, subcritical

(b) Angle of attack = 38 degrees

Figure 2: Waterfall plots of wake velocity spectra

Capillarity and Drops

Capillarity and elasticity

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May 18, 2009

In this talk, we will present different situations where a fluid at rest may deform an elastic solid : through capillary forces in the presence of interfaces. Although at macroscopic scale, surface tension has often little effect on a solid, we will show that capilarity becomes a major effect at small scale, or when using very flexible objects.

The effect of surface tension on a given structure depends on its *elasto-capillary length* , a paramter that combines bending rigidity and surface tension. We will discuss some simple experiments to measure this important parameter.

We will then review different problems where slender objects are deformed when fluid interfaces are present : Can the capillary sticking of slender objects (a major limiting factor for micro-structures) may be avoided. How can a flexible rod pierce a liquid interface without buckling? Can we use surface tension forces to fold micro-structures (capillart origami)?

We will also present some open questions for the more difficult case of capillary deformation of thin plates...

Dynamical Origami

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Christophe Josserand, Institut J-L-R D'Alembert josseran@lmm.jussieu.fr
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Origami is the Japanese name for the art and science of folding. The different structures that one can observe in traditional Origami and in nature have long fascinated biologists, physicists and mathematicians. For instance, physicists see in them the intriguing interactions between geometrical singularities and the elastic properties of the material. Natural exemples of folding include birds wings, flowers petals, leaves, and are related to growth or packing processes. In industry, beside the unfolding of solar panel arrays for space satellites, micro-technology aims to developp smaller and smaller patterns and structures. Using adapted and well controlled forces at small scales remains thus an important issue. While the description of origami has been so far mostly limited to equilibrium or quasi-static configurations, we perform here rapid folding of elastic thin sheets. These highly dynamical origami are achieved by means of drop impacts on elastic flat sheet. In this configuration, the driving forces controlling the folding are surface tensions and inertia of the impacting drops. The role of the latter is quite subtle as it first transforms into surface energy during the drops spreading. As a result, the large drop interface increases the efficiency of surface tension and its role in the retraction process.
Changing the drop (radius, velocity…) or the elastic sheet (thickness, patterns…) properties allows for a large variety of results : cylindrical shapes, partial or total folding…This rich complexity of dynamical origami has a very interesting consequence: for a given shape of elastic sheet, one can control the folding dynamics by changing the impacting drop characteristics. This shape selection by dynamical process can be observed in figure 2, where the same PDMS sheet can form a cylinder, a 2-folds or a 4-folds structure depending on the impact conditions (see movies here [partial_folding.mov],[cylinder.mov],[pyramidal.mov]).

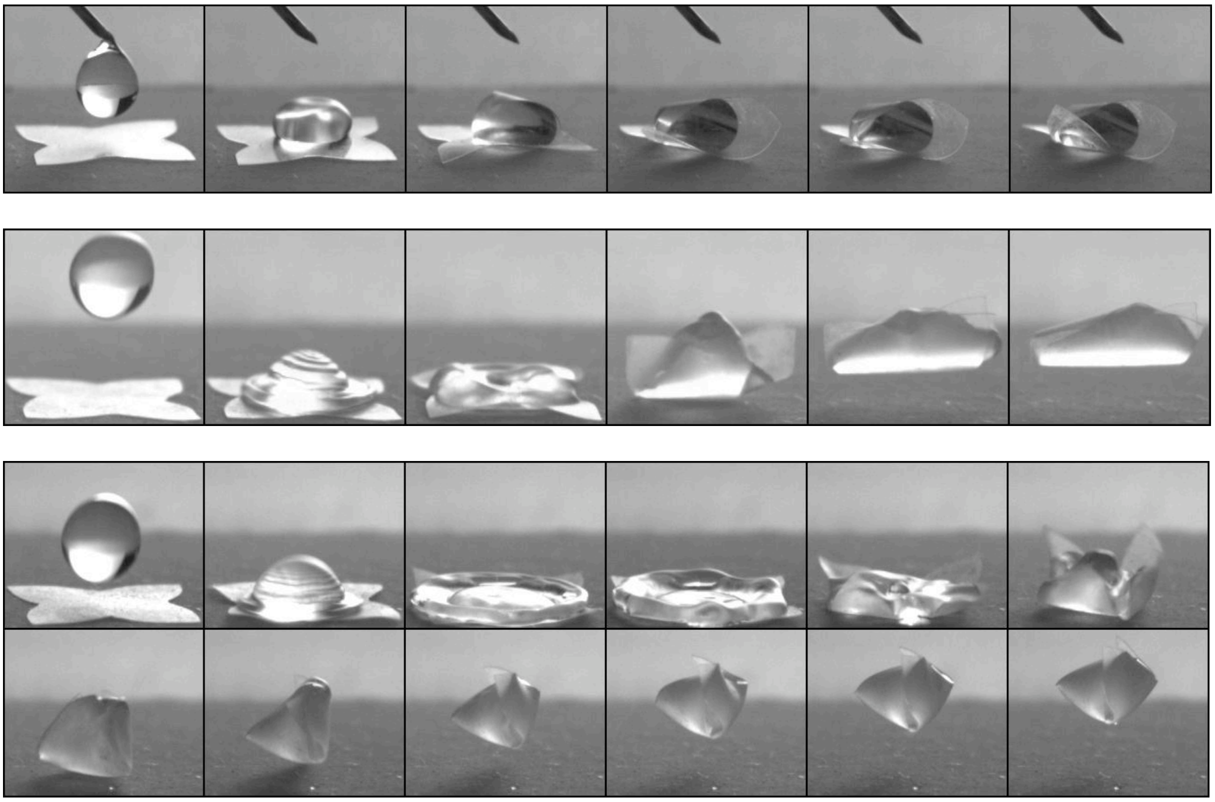

Figure 2 : Illustration of shape selection when a drop impacts on the same elastic pattern.

Actuating capillary origami with electrowetting

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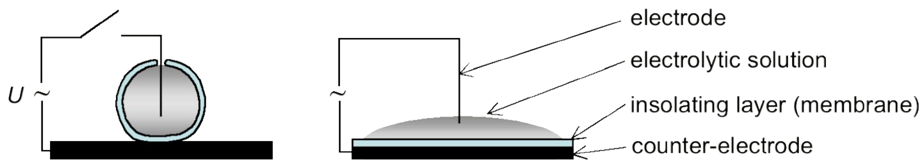
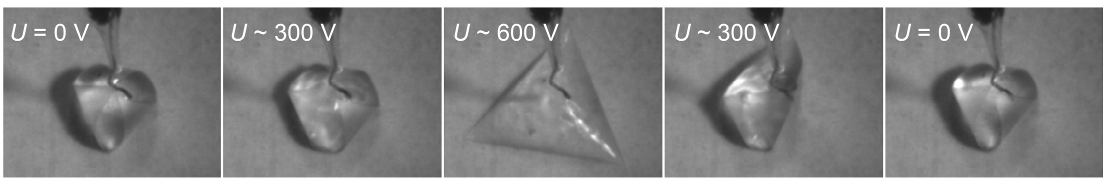
What happens if a water droplet is deposited on a flexible sheet? Does the sheet spontaneously wrap around the droplet? Yes, it does if the capillary forces from the water/air interface overtake the bending resistance of the elastic sheet (Py *et al*. 2007). This "capillary origami" technique may be used to encapsulate micro-droplets but also to produce 3-dimensional shapes from planar templates, which is a challenge at the scale of Micro-Electro-Mechanical-Systems.

Once the 3D structure is closed, would it be possible to open and close it again at wish? The wetting properties of a liquid can be tuned by applying an electric field (Mugele & Baret, 2005). This phenomenon, known as electrowetting, can be interpreted as the minimization of the electric energy of a capacitor. As a way of actuating the shape of the origami, we propose to apply an electric field between the droplet (an electrolytic solution) and the substrate. The flexible sheet then isolates both electrodes (the liquid droplet and the ground substrate). Without electric field, the droplet remains encapsulated, and it opens as a field is applied.

We pretend to describe this original interaction between an electric field, capillarity and elasticity.



Re-opening of an encapsulated droplet actuated by an electric field.



Preliminary experiment successfully achieved by Fabien Closa and Charlotte Py.

References:

C. Py, P. Reverdy, L. Doppler, J. Bico, B. Roman & C.N.Baroud, "Capillary origami: spontaneous wrapping of a droplet with an elastic sheet", *Phys. Rev. Lett.*, **98**, 156103 (2007).

F. Mugele & J.-C. Baret, "Electrowetting: from basics to applications", *J. Phys. Cond. Mat.*, **17** R705 (2005).

Energy criteria for elasto-capillary wrapping

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We consider the interaction between a liquid drop and a flexible membrane, a fluid-structure problem where capillarity plays the major role. A recent work [1] has shown that surface tension may be used to bend an elastic membrane if the typical scale of the membrane is above a critical length. Here, we first discuss some more detailed experimental measurements that demonstrate the switching between different modes of folding and also a dewetting transition during the folding of the membrane. A model based on minimal ingredients is then developed. This model is based on an energetic approach and may be used to account for all of the observed phenomena. Contrary to more refined modeling, the minimal model may be extended to more complex cases with little extra work, making it useful for complex geometries or in order to include further phenomena.

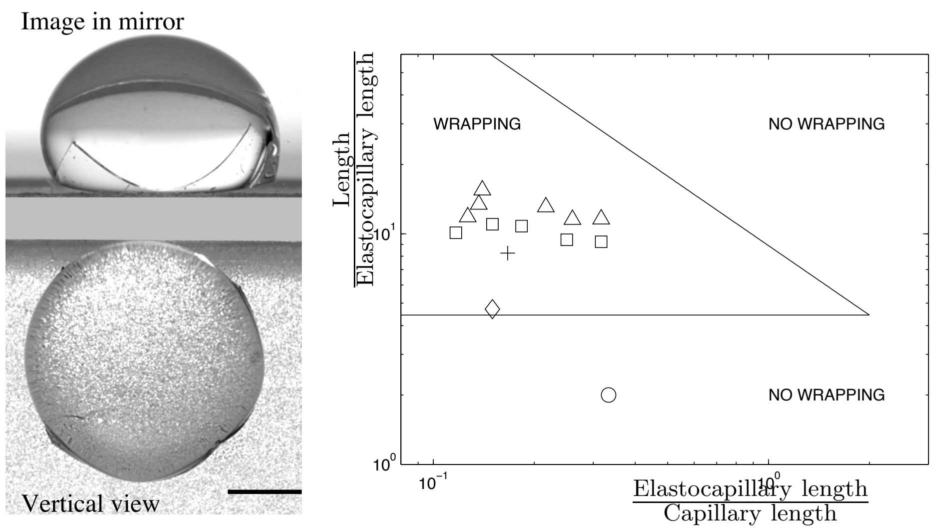

Fig. 1: Left : experiment on wrapping of a droplet by a square membrane (top and side wiew). Right : the criteria for wrapping derived from simple energy considerations. Symbols correspond to all wrapping experiments decribed in [1], made with various shapes of membranes.

[1] Py, C., Reverdy, P., Doppler, L., Bico, J., Roman, B., Baroud, C. N., 2007. Capillary origami: Spontaneous wrapping of a droplet with an elastic sheet. Phys. Rev. Lett. 98 (15), 156–103.

Soap films burst like flapping flags

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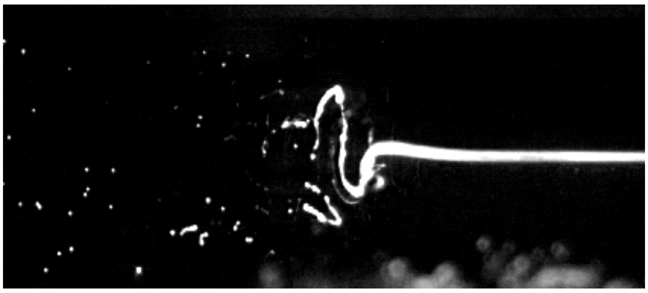
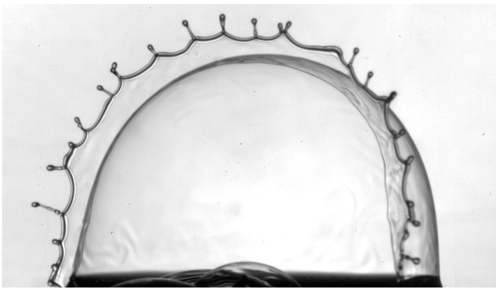
When punctured, a uniform liquid sheet is known, since Taylor and Culick, to recess at a constant speed balancing surface tension and inertia. For planar soap films, Marangoni surface tension elasticity due to surfactants drives the rim shape and its inner flow. It leads to an extended rim, called "aureole", where the film thickens and the liquid is gradually set into motion. This steady solution holds until the initially smooth receding rim is violently destabilized, exhibiting deep indentations from which droplets are ejected. A surprising new three dimensional mechanism explaining this destabilization and resulting wavelength has been evidenced : because of the shear between the still outer medium and the receding liquid, the film flaps through a Kelvin–Helmholtz instability, itself inducing an acceleration perpendicular to the film, which intensifies with the flapping amplitude. To this acceleration is associated a classical Rayleigh–Taylor mechanism, promoting the rim indentations. The same mechanism holds for a punctured round bubble, for which the relevant acceleration is the Culick velocity squared divided by the bubble radius. The bearing of this phenomenon on aerosols formation in Nature will be underlined.



(a) Flapping flag-like motion of a planar soap film receding edge.



(b) Centrifuged ligaments of a bursting water bubble.

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Splashing on elastic membranes: The importance of early-time dynamics

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We study systematically the effect of substrate compliance on the threshold for splashing of a liquid drop using an elastic membrane under variable tension. We find that the splashing behavior is strongly affected by the tension in the membrane and splashing can be suppressed by reducing this tension (see Fig. 1). The deflection of the membrane upon droplet impact is measured using a laser sheet, and the results allow us to estimate the energy absorbed by the film upon drop impact. Measurements of the velocity and acceleration of the spreading drop after impact indicate that the splashing behavior is set at very early times after, or possibly just before, impact, far before the actual splash occurs. We also provide a model for the tension dependence of the splashing threshold based on the pressure in the drop upon impact that takes into account the interplay between membrane tension and drop parameters (see Fig. 1b).

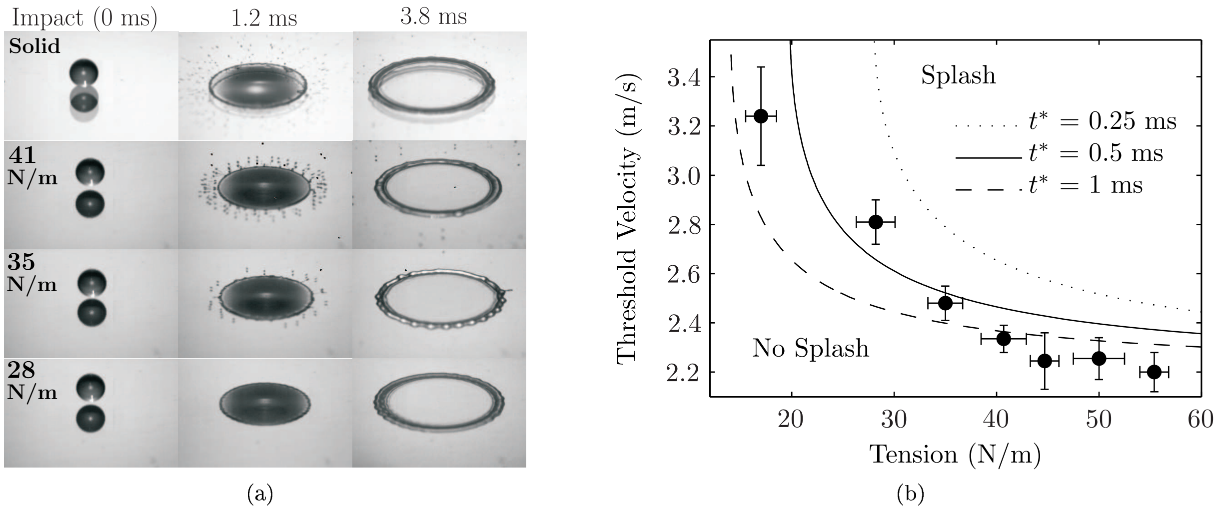
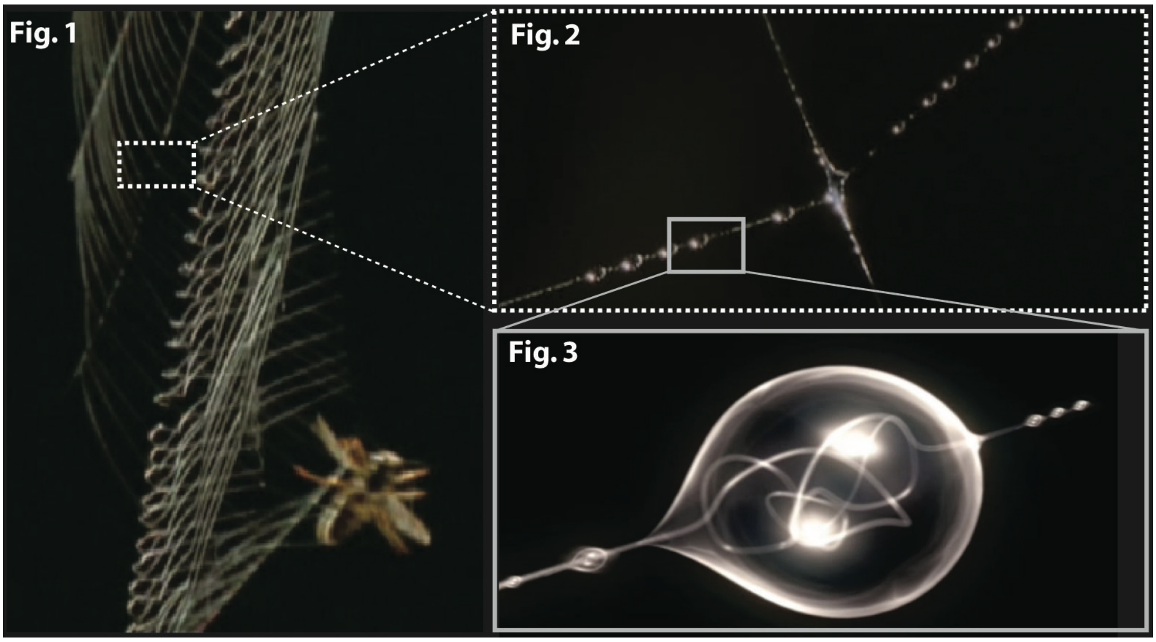


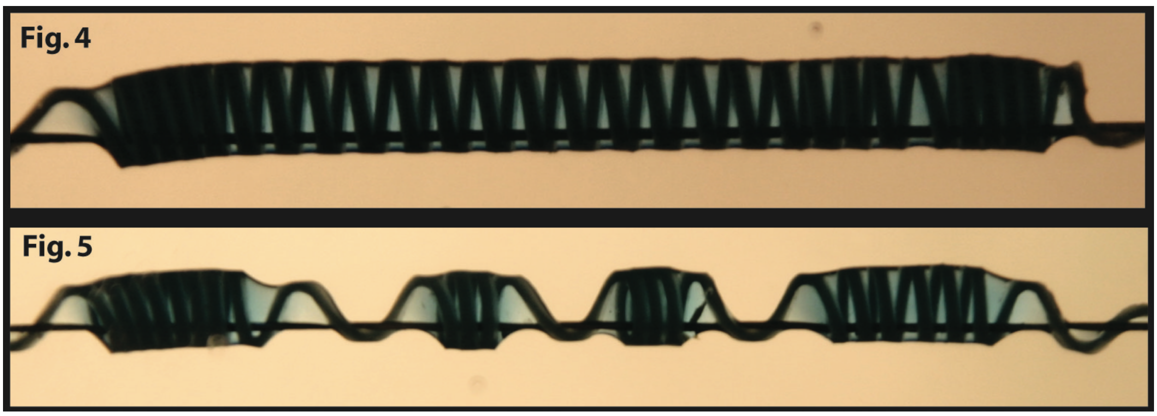
Figure 1: (a) High-speed images of drop impact ($R_0 = 1.01 \pm 0.02$, $V_0 = 2.5 \pm 0.1$ m/s) on membranes of varying tension. Each row shows the drop at three times: just before impact, 1.2 ms, and 3.8 ms after impact. The top row is for impact on a solid (plastic petri dish). (b) Threshold velocity for splashing versus membrane tension for drops with $R_0 = 1.01 \pm 0.02$ mm. Error bars show the transition regime - above the top error bar, splashing always occurs; below the bottom error bar, splashing never occurs. The lines are calculated from our model for tension dependence of the splashing threshold for several critical times, t^*, after impact.

Spider capture thread: form and function

John W. Bush and Sunghwan Jung (Department of Mathematics, MIT)
Christophe Clanet (Laboratoire Hydrodynamique, Ecole Polytechnique)

We present the results of a combined theoretical and experimental investigation of spider capture thread. The spider capture threads that run circumferentially around some spider webs are coated with a viscous fluid. Capillary instability of this film prompts its evolution into a series of fluid droplets, inside of which the slack elastic thread wraps into a series of coils. The result is a characteristic windlass mechanism: when the prey strikes the web, the coil unravels within the drop, and the associated viscous damping prevents the prey from being ejected. (Figures 1-3. Images courtesy of the BBC's “Life in undergrowth”). Analogue laboratory experiments mimic the instability of the spider web responsible for its subtle form (Figure 4-5). Elastocapillary instability of a helical elastic thread immersed in silicone oil results in a wavelength prescribed by the interfacial tension and the spring's initial loading.





Falling drops over elastic sheets

Alexandre Ponomarenko, Christophe Clanet and David Quéré
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Leaves of trees under the rain provide the most common example where drops hit flexible surfaces, a situation we tried to describe and understand, in the perspective of plant treatments or disease dissemination, for example. Hence we studied the impact of drops over elastic sheets, for Weber numbers typically between 0 and 600, and various solid rigidities. In the figure below, we show an example of such an impact, as captured with a high-speed camera.

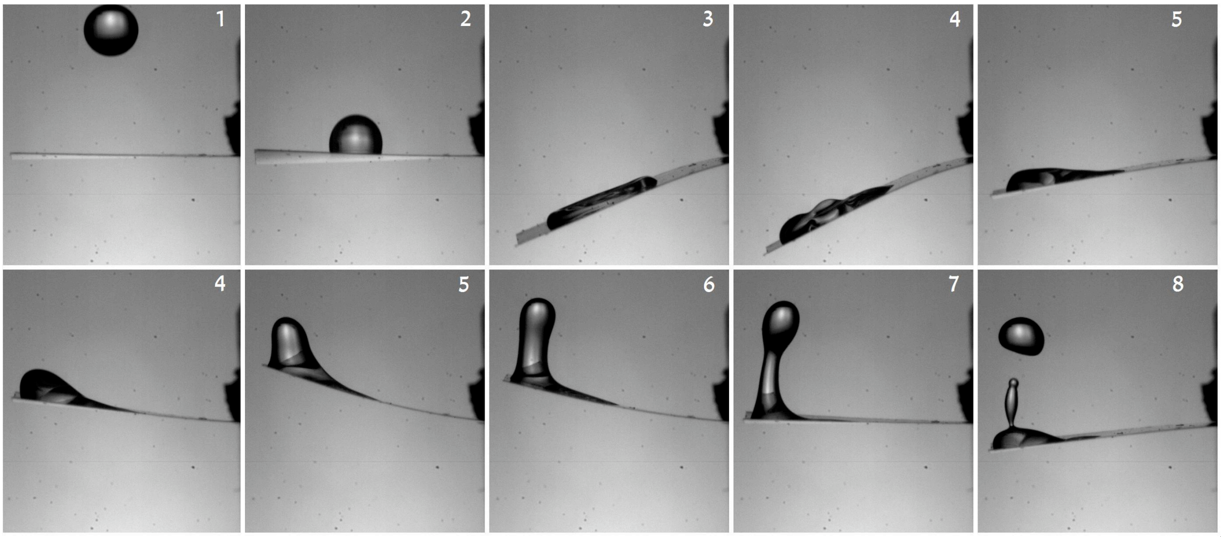

FIG. 1: Impact of a water drop ($D_0 = 2.5$mm, $U_0 = 1.43$m.s^{-1}) over a flexible sheet (rigidity : $\mu = 7.10^{-6}$N.m^2). Time interval between the pictures : 4 ms.

As for an impact over a rigid surface, the drop deforms after hitting the surface, reaching a maximal diameter. In the same time, the surface bends, which makes it oscillate as the drop recoils : in some cases, part of the drop can be ejected, despite a wetting situation favourable to its capture by the solid surface. We discuss quantitatively the different characteristics of this impact, and emphasize more particularly the features specifically related to the elasticity of the substrate.

Grabbing water with thin elastic sheets: the elasto-pipette

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December 19, 2008

Py *et. al.* [1] have recently shown that the coupling between surface tension and elasticity of thin sheets can be used to induce self-assembly of flat elastic objects into three dimensional structures: *capillary origami* at play. Here, we present the results of a combined experimental and theoretical investigation of a related system in which a thin and petal-shaped elastic plate is withdrawn from the flat interface of a liquid bath. A representative sequence of this process is presented in Fig. 1 where the flat thin plate is driven towards the liquid interface (a-d) and then is pulled away from it (e-h). As the plate is drawn upwards, it deforms due to interfacial and hydrostatic forces, up to a point where it completely detaches from the interface. If the bending stiffness of the plate is sufficiently low, upon detachment a regime can be attained where the petal-shaped plate can fully enclose and therefore *grab* a drop from the liquid bath, as shown in Fig. 1h). We propose this mechanism as a robust means by which to grab, manipulate and transport small fluid droplets.

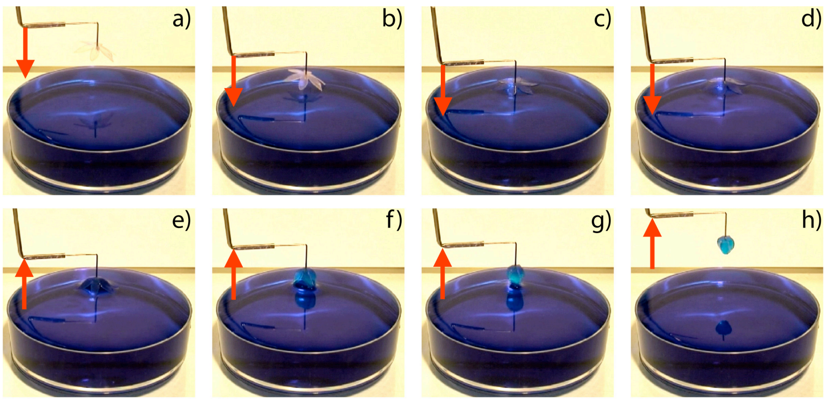

Figure 1: A thin petal-shape plate is put in contact with a liquid interface (a-d) and is then drawn upwards from it (e-h). The red arrow points in the direction of motion. The flowers are cut to a diameter of $10mm$, out of a thin (250μm) vinylpolysiloxane sheet. The fluid used is water dyed with blue food coloring.

[1] C. Py, P. Reverly, L. Doppler, J. Bico, B. Roman and C. Baroud, *Phys. Rev. Lett.* **98**, 156103 (2007).

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Impacts on thin elastic sheets

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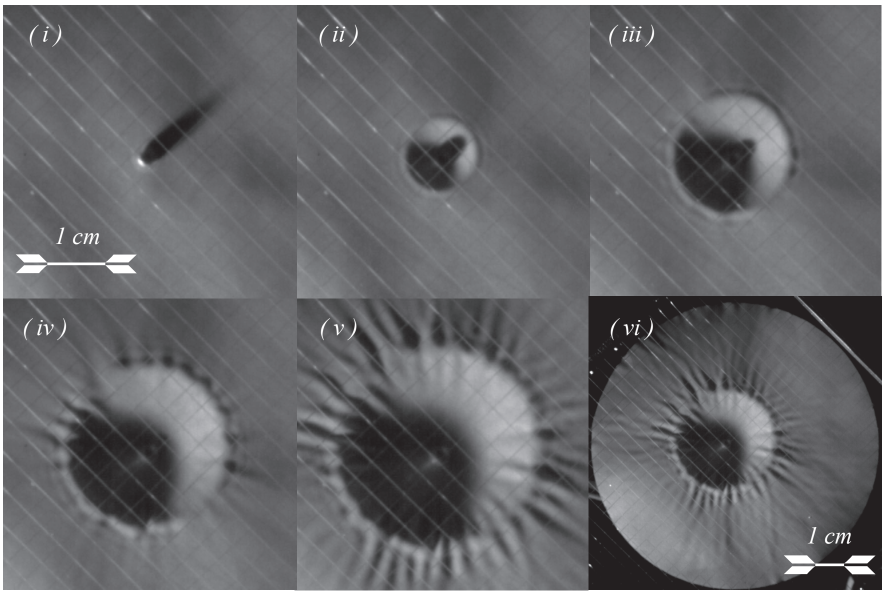
We study transverse impacts of rigid objects on a free elastic membrane, using thin circular sheets of natural rubber as experimental models. After impact, two distinct axisymmetric waves propagate in and on the sheet. First, a tensile wave travels at sound speed leaving behind the wavefront a stretched domain and then a transverse wave propagates on the stretched area at a lower speed. In the stretched area, geometrical confinement induces compressive circumferential stresses leading to a buckling instability, giving rise to radial wrinkles.



We report on a set of experiments and theoretical remarks on the conditions of occurrence of these wrinkles, their dynamics and wavelength. We will also describe the dynamics of the impacted membrane when it stands on a liquid substrate. Finally, we briefly discuss the rayed craters resulting from meteorite impacts observed on the Moon and on Mars for example.

Flow-Induced Vibration

Plant dynamics under wind load : strategies and solutions

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Wind is the main abiotic stress on plants. It may also be a positive environmental factor in its role in seed dispersal or in thermal equilibrium of the plant. One may expect that in the course of evolution the mechanical structure of plants and of plant organs have somehow adapted to minimize the negative effects of wind and maximize its positive effects. This is a widely unknown field, because of the immense variety of plans.

Understanding the interactions of wind and plants is useful in many aspects [1]. First, plants are our main resource of food and they play an essential role in water and oxygen balance on earth. They are also used as materials for building or manufacturing objects all over the world. Therefore, their vulnerability to wind does affect our lives, in the short and long terms. Second, plants display a variety of architectural and mechanical organisation that is so large that one may expect that some efficient solutions exists that may be of some use to us. This also applies to the interaction between aquatic plants and flow related to current or waves. Finally, plant systems are much less studied than animal systems, though they are in many biological aspects much simpler.

From a mechanical point of view, plants must cope with two aspects of external flow : the static component and the dynamic component. Flow-induced static drag may cause high stress in plant tissues, causing irreversible damage. High amplitude vibrations may cause damage by fatigue of tissues, of plant/ground connections, or impact and abrasion between plants. In a man-made structure, the strategy to avoid damage by static loads is generally to stiffen the structure. To avoid the effect of dynamic loads the strategy is to damp the structure. These strategies are not taken by plants, than cannot easily produce large quantity of biomass to stiffen structures, and do not have a large variety of possible tissues that they can use for damping or stiffening.

The issue of static load is generally addressed by plants in two ways. First, their growth is affected by wind in such a way that resistance to such loads is certainly increased : plants under wind grow shorter and with a higher allocation of biomass in roots. This is a complex biological mechanism, see for instance [2]. The second way is the ability of plants to passively change shape under wind load and thereby reduce their drag. This is a well known phenomenon called drag reduction by reconfiguration. The idealized case of drag on a flexible plate is presented in another paper of the same conference [3]. The extreme case of irreversible reconfiguration is also worth of interest : plants may loose parts of their structure if this is the condition to survive, as they are able to re-grow from broken parts.

The issue of dynamic loading is more complex : first, the dynamic excitation by wind differs in the case of an isolated plant or a plant inside a canopy. In the first case the excitation is typical of low atmospheric boundary layer turbulence, while in the second a specific mixing layer instability dominates. Second, the architecture of plants significantly affects their dynamical properties : beam-like shapes such as grass leaves or pine trees, or branched forms such as most trees. In the case of branched trees, it has been observed that modal frequencies of the trunk and of the main branches are close. This has recently been recently shown to be the natural consequence of the allometric laws that define the organisation of length and diameters in such systems [4]. The main issue is now to establish whether or not there is a control by the plant of its modal frequencies during growth. If this is the case, it might be a mechanism to enhance energy transfer between modes and thereby reduce oscillation amplitudes [5]. Recent experiments on poplar shoots showed that the frequency of oscillation remained constant during growth as long as both apical and diameter growth exist. In the case of canopies made of beam-like plants, such as most crops or seaweeds, a specific interaction takes place : the flexibility of the canopy does modify the dynamics of flow through it, by a mechanism similar to lock-in in vortex-induced vibrations. This results in enhanced motion of the canopy [6].

As a conclusion, one may say that plants seem to have developed strategies and solutions to cope with wind loads that are quite different from those used in engineering of man-made structures. This is clearly a new field for biomimetics applications.

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[2] Moulia B, Coutand C, Lenne C. 2006. Posture control and skeletal mechanical acclimation in terrestrial plants: implications for mechanical modeling of plant architecture. American Journal of Botany. 93:147789

[3] F. Gosselin, E. de Langre Drag reduction by reconfiguration of flexible plates, in this conference, *see also F. Gosselin, E. de Langre and B. Machado-Almeida. Drag reduction of flexible plates by reconfiguration. Submitted to Journal of Fluid Mechanics. (2009).*

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Flapping of flexible membranes in high-*Re* flows and applications to locomotion

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To move in their environment, insects and fishes must generate propulsive and/or lift forces from the flapping of their wings or fins in the surrounding fluid. These flapping structures are in general flexible, with bending rigidities ranging over several orders of magnitude depending on the species. The study of flexibility's influence on thrust creation and propulsion efficiency is therefore critical to the understanding of biological locomotion at high Reynolds number.

We consider a simplified two-dimensional model to study the influence of flexural rigidity on flapping efficiency based on potential flow theory. Flow separation at the trailing edge of the flapping membrane and the vortical wake are accounted for by the shedding of unsteady (Brown–Michael) vortices. This fluid representation is coupled to a one-dimensional inextensible Euler–Bernoulli beam model. This approach allows us to capture the strongly unsteady nature of vorticity shedding by the membrane and the nonlinear flapping regime. It has recently been used to study the flapping flag instability and obtained results in good agreement with previous analytical and experimental results [1].

We extend this model here to study the dynamics of a passive membrane placed in a uniform flow and forced at its leading edge in a purely heaving motion. We are interested in the influence of the solid rigidity on the propulsion performance (mean thrust, required power input and efficiency) and the wake characteristics. The introduction of flexibility is shown to be able to increase the flapping efficiency in comparison to the purely rigid wing.

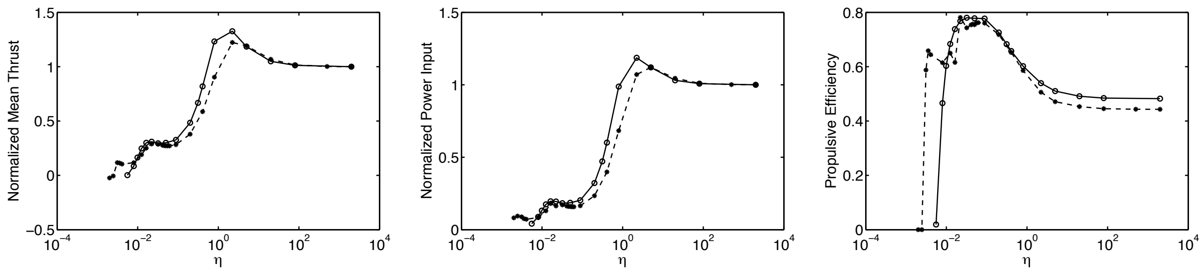

Figure 1: Evolution of the mean thrust (left), mean power input (center) and flapping efficiency (right) with the non-dimensional rigidity $\eta = B/\rho U_\infty^2 L^3$ for a flexible membrane with mass ratio $\mu = \rho_s/\rho L = 0.2$ with non-dimensional heaving frequency $\bar{f} = fL/U_\infty = 0.32$ and flapping amplitude $\epsilon = A/L = 0.1$ (solid) and $\epsilon = 0.5$ (dashed).

[1] S. Michelin, S. G. Llewellyn Smith, and B. J. Glover. Vortex shedding model of a flapping flag. *J. Fluid Mech.*, 617:1–10, 2008.

Effect of dissipation on local and global stability of a fluid conveying pipe

Abstract for FE2009

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January, 1, 2009

The fluid conveying pipe is often considered as a model problem for numerous physical systems where the dynamics of a structure is coupled to an axial flow. This system is known to become unstable at a critical velocity, by flutter or buckling, depending on various mechanical parameters and boundary conditions. Two different approaches are used to describe the properties of such one-dimensional systems. When the system is sought infinite, the waves propagating in the medium are considered through the analysis of the local wave equation. If temporally or statially amplified waves are identified, the system is said to be *locally* unstable. When the same medium is of finite length, the modes are studied, through the analysis of the same local wave equation, associated with boundary conditions. If a temporally amplified mode is found, the system is said to be *globally* unstable.

The comparison of local and global stability properties has been done on various systems by several authors, and one main result is that when the length of the system is increased, the critical velocity for global instability tends to a limit that corresponds to a local criterion. However, no unique local criterion can predict the global instability of these long systems. Depending on medium and boundary conditions characteristics, it can be that of absolute instability, local instability or that of existence of static or dynamic neutral waves. In the present work, the effect of dissipation on local and global instabilities is investigated. Two particular problems are studied, the fluid conveying pipe resting on an elastic foundation, and the fluid-conveying pipe subjected to tension.

The local stability analysis is conducted by studying the dispersion relation. For the fluid-conveying pipe, dissipation is found to have a stabilizing or destabilizing effect, depending on the parameters. It is then shown that destabilization by dissipation originates from the existence of negative energy waves.

To study the global stability properties of these systems, Galerkin computations are used. In particular, the complex global eigenfrequencies of the system are computed. This allows to compute marginal stability curves in the domain of parameters. In absence of dissipation, complementary results are obtained with respect to previous studies. When dissipation is added, it is predicted that the criterion for global instability of long systems is the neutral static range criterion, which is confirmed by Galerkin computations. Finally, two characteristic lengths are defined. One is based on the rigidity term (tension or elastic foundation), the other is based on dissipation. Depending on the respective values of these lengths and of the value of the length of the system, criterion of global stability is found to be that of local stability without dissipation or local stability with dissipation (see Figure 1).

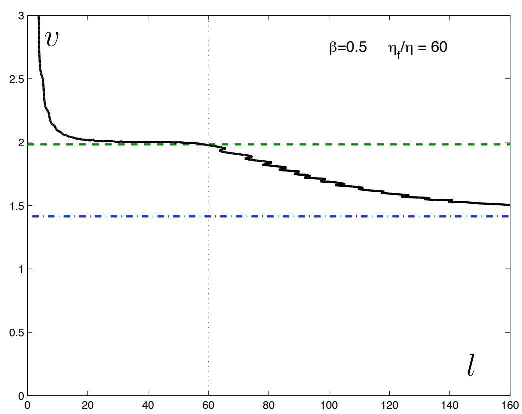

Figure 1: *Fluid conveying pipe on elastic foundation with dissipation : non dimensional critical velocity for global instability as function of the non dimensional length l in a typical case where two different local criteria apply depending on l.*

In conclusion, it is found that dissipation drastically changes the global stability criteria of fluid-conveying pipes. Most of the time, dissipation has a destabilizing effect, due to the destabilization of negative energy waves.

Three−dimensional Simulation of a Flapping Flag in a Uniform Flow

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In the present study, a three−dimensional simulation of a flapping flag in a uniform flow was carried out by the immersed boundary method [1,2]. In the proposed method, a direct numerical scheme is developed to calculate the flag motion, with the elastic force treated implicitly, while the fluid motion defined on an Eulerian grid is calculated using an efficient Navier−Stokes solver. A series of numerical tests were performed to study the dynamics of the coupled system. When the gravity force is excluded, the flag preserves symmetry about its centerline when flapping at moderate Reynolds numbers, while asymmetry arises from the fluid instability as Reynolds number increases. It was also observed that the flag flaps almost uniformly along the spanwise direction when the flag inertial force is dominant over the fluid viscous force (see Fig.1), while the bending of the trailing edge becomes more obvious at low Reynolds number. The vortical structure shedding from the trailing edge connects those from the side edges to form a 'hairpin' structure with two antennae, as shown in Fig.2. After including the gravity force, the sagging-down of the flag and the rolling-up of the upper-corner deform the vortical structures. More results, e.g. the effect of the aspect ratio and the stability boundary for the onset of flapping, will also be presented.

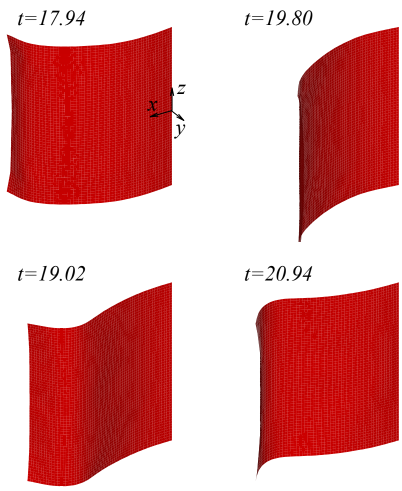

Fig. 1. Instantaneous flag positions at Re=200

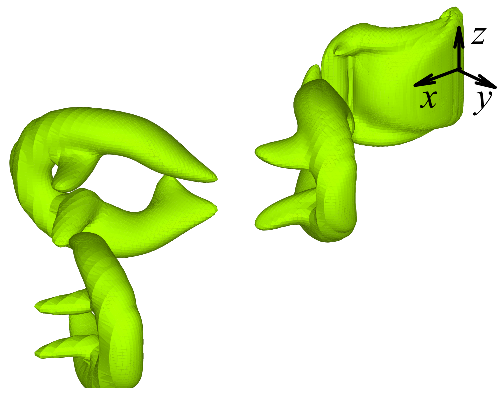

Fig. 2. Vortical structures shedding from the flapping flag at Re=200.

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The flapping-flag instability as a nonlinear eigenvalue problem

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We reconsider the classical problem of the instability of a flapping flag in an inviscid background flow with a vortex sheet wake, and reformulate it as a nonlinear eigenvalue problem. We solve the problem numerically for the 20 lowest wave number modes. We find that the lowest wave number mode is the first to become unstable, and has the fastest growth rate within 3.5 decades of the stability boundary in the parameter space of flag mass and flag rigidity. This and subsequent modes become unstable by merging into complex-conjugate pairs, which then lose conjugacy further into the region of instability. Eigenmodes exhibit sharp transitions in shape across the stability boundary. In the corresponding initial value problem, we show a correlation between the wave number of unstable modes in the small-amplitude (growth) regime and the large-amplitude (saturation) regime. Wave number increases with decreasing rigidity and shows a combination of discrete and continuous change in the shape of unstable modes. Using an infinite flag model we compute the parameters of the most unstable flag and show that a classical mechanism for the instability correlating pressure lows to flag amplitude peaks does not hold.

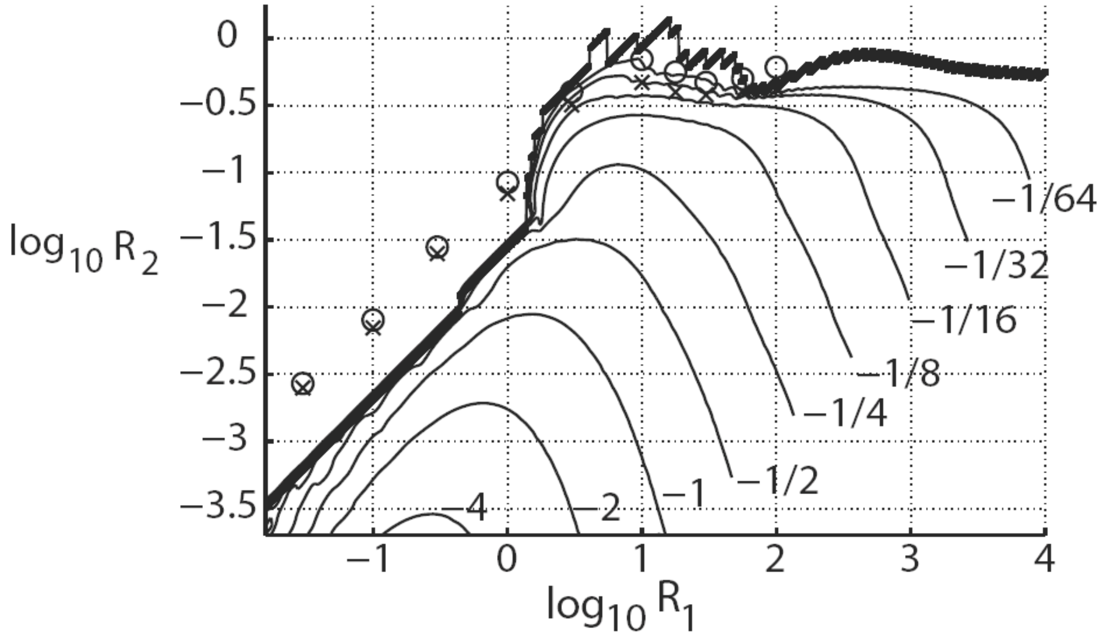

FIG. 1. The region in $R1$-$R2$ space in which the flag is linearly unstable. The thick black line marks the location of the linear stability boundary. The vertical resolution of the data is approximately half the size of the jumps in the zigzag line. The horizontal resolution of the data is finer: one data point for every multiplicative change of 1.01 in $R1$. The contours below the stability boundary give the value of the imaginary part of the eigenfrequency corresponding to the most unstable mode. Plotted also are large circles and crosses, which represent the stability boundary computed numerically in Alben & Shelley (2008).

Abstract for the International Conference on Fluid and Elasticity
23-26 June 2009, Carry-le-Rouet, France

The motion and sound of a forced flag

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The prevailing view of the dynamics of flapping flags is that the onset of motion is caused by temporal instability of the initial planar state [1,2]. We examine this view by considering the linearized two-dimensional forced motion of a flag immersed in a high-Reynolds number flow and subject to forcing by a 'street' of vortices shed quasi-periodically from its cylindrical pole [3] (Figure 1). First, the zone of nominal instability is delineated, by the solution to an eigenvalue problem for the self-induced motion (in the absence of shed vortices). Forced motion is then analysed by introducing the flag-pole wake as a forcing term in the equation of motion. It is found that this motion is possible even under conditions where the unforced flag is still nominally stable. The results obtained are used to evaluate the sound produced by the motion and are compared with our previous predictions of the acoustic radiation by an unforced flag [4].

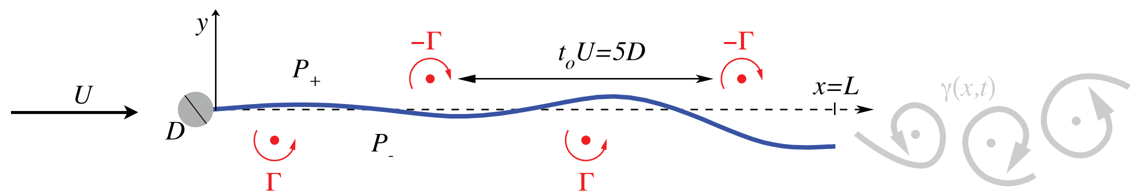

Figure 1: Schematic setup of the problem. The flag cylindrical pole of diameter D is connected to the flag at $x = 0$. The free end is at $x = L$. The inertial fluid loading owing to flag motion is $\Delta P = P_- - P_+$ and the trailing-edge vorticity is $\gamma(x,t)$. The vortices shed from the flag pole convect along $y \approx \pm D/2$ at speed U. Their strength Γ and frequency $f_0 = 1/t_0$ are determined by the mean flow speed U and pole diameter D [3].

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Bifurcations and periodic regimes in woodwind instruments

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Woodwind musical instruments (e.g. clarinet, saxophone) are nonlinear dynamical systems and, as such, address numerous important physical questions. These instruments encounter phenomena such as Hopf bifurcations, period doubling and Neimark-Sacker bifurcations. The blowing pressure initiated by the instrumentist controls the existence and amplitude of the oscillating regime, giving the musical sound. A great challenge is to relate the physical parameters of both the instrument and the player to the characteristics of the sound.

These instruments are made of a resonator (cylindrical or conical tube), a cane reed which can vibrate through a nonlinear fluid structure interaction. Acoustics inside the resonator is modeled by the wave equation (one spatial dimension) with appropriate boundary conditions. A source term describing the interaction with the volume flow is also present. The reed is modeled as a mass-damper-spring device relating the opening of the mouthpiece with the internal acoustic pressure. The static Bernouilli relation couple nonlinearly the volume flow, the air pressure and the tip opening.

Assuming a periodic solution, relationship in the frequency domain have been established from the differential equations modeling this system. The study of the small oscillating regime in the frequency domain has given several analytical expressions on the oscillation threshold, nature of the bifurcation, and estimation of the amplitude of the harmonics. The reed-resonator coupling gives rise to several possible oscillating solutions corresponding to different notes of the instrument for the same fingering. Each solution at small oscillation is the beginning of a branch in the bifurcation diagram. It can either be stable or unstable depending on the value of the mouth pressure (bifurcation parameter). The choice of the solution is determined by the initial conditions.

The behaviour at large oscillation may be only partly related to the small oscillation regime as branches in the bifurcation diagram can appear from oscillating solution of large amplitude (period doubling or Neimark-Sacker bifurcation). The analytical approach, which studies the bifurcations of the steady state regime, cannot explain the complete behaviour of woodwind instruments. Numerical simulations have been run to investigate further the problem. Firstly, the bifurcation diagram can be derived by a frequency domain approach based on the harmonic balance technique. It suggests the existence of bifurcations of oscillating solutions. Secondly, a time domain simulation confirms the previous results. Moreover, it shows the selected oscillating solution, among the several theoretical possible ones, depending on the initial condition.

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FLOW SEPARATION IN FLOW-INDUCED VIBRATION OF HUMAN VOCAL FOLDS

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In spite of large progress in fundamental research of voice production during recent years, some features are not yet fully understood. The concept of fluid-structure interaction between glottal flow and elastic vocal folds relies on good knowledge of aerodynamics and, among others, on the dynamics of the glottal jet and its separation from the vocal fold surfaces, inducing vortex shedding from the boundary layer.

Due to periodical closure of the glottal channel during vocal fold vibration and inherent unsteadiness of the airflow, the aerodynamic effects in glottis are very complex. Yet the simplified flow models of vocal folds, usually disregarding flow separation in the divergent part of glottis and thus considering unrealistic pressure distributions along the vocal folds, are still widely used due to their computational efficiency. Experimental data on flow separation in glottis has been lacking, too.

This paper presents an experimental study providing quantitative data on the position of the flow separation point, trying to estimate its influence on flow-induced vibration. Data was measured using a PIV system on a scaled physical self-oscillating vocal fold model, whose shape was specified according to measurements on excised human larynges (Šidlof et al. 2008). The position of the flow separation point during the vocal fold vibration period was evaluated, analyzed and plotted using a semiautomatic procedure for different flow velocities.

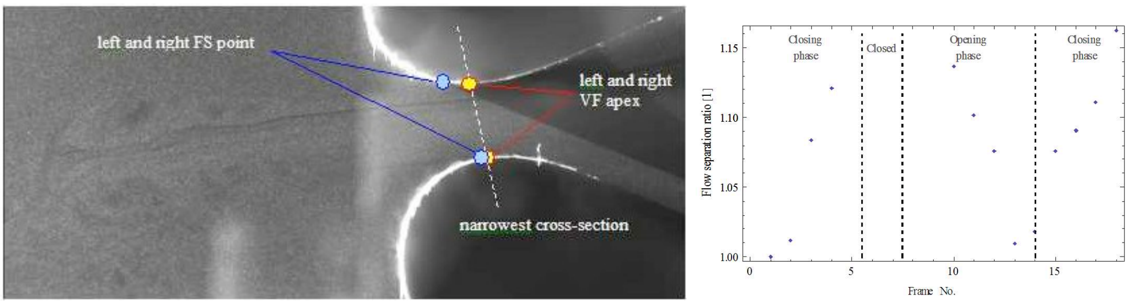

Figure 1: (a) First of two PIV frames showing the flow between vocal folds. When played successively, the position where the jet separates from the vocal fold surface is clearly visible. (b) "Flow separation ratio": vertical distance of the left and right flow separation point divided by minimum orifice width.

Acknowledgements

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Internal Flows

Theoretical and computational analysis of flow in collapsible tubes

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In many physiological systems, viscous fluids are transported via networks of elastic tubes which can deform significantly in response to the traction that the fluid exerts on them. If the vessel is subjected to a sufficiently large negative transmural (internal minus external) pressure, it buckles non-axisymmetrically. In this regime, small changes in transmural pressure cause large changes in its cross-sectional area. The resulting changes in the flow field can lead to strong fluid–structure interaction which is responsible for a variety of physiological phenomena such as flow limitation during forced expiration, and the development of Korotkoff sounds during sphygmomanometry.

Most experimental studies of flow in collapsible tubes are performed using a Starling Resistor: a pressure chamber that encloses a finite-length elastic tube mounted between two rigid tubes. One of the most intriguing features of this system is its propensity to develop large-amplitude self-excited oscillations of great complexity when the Reynolds number of the flow exceeds a certain critical value.

This talk will provide an overview of recent progress on the theoretical and computational analysis of flow in the Starling resistor, focusing on a particular parameter regime in which the system performs self-excited oscillations of high frequency. Following a brief discussion of the mechanism responsible for the onset of the oscillations, I will compare theoretical predictions for the system's behaviour, such as the critical Reynolds number beyond which self-excited oscillations develop, against results from direct numerical simulations which also allow us to follow the growing oscillations into the large-displacement regime.

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An added-mass free semi-implicit coupling scheme for fluid-structure interaction arising in blood flows

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Abstract

In the context of blood flow simulations in large vessels, numerical difficulties might be expected since fluid-structure interaction with a viscous incompressible fluid is involved. These are due to the so-called added-mass effect, when fluid and solid densities are close and/or when the domain is slender [4]. To circumvent them, we propose a semi-implicit coupling scheme for fluid-structure interaction [1]. Its efficiency is based on the explicit splitting of the viscous effects and geometrical/convective non-linearities, through the use of the Chorin-Temam projection scheme within the fluid [5]. Stability is ensured by the implicit treatment of the pressure stresses and by the treatment of the viscous coupling by a Nitsche-based mortaring [2,3]. *A priori* energy estimations are derived to prove theoretically that the scheme is stable, irrespectively of the added-mass effect, and with possibly a conservative time-stepping within the structure. Numerical results in two and three dimensions did confirm these stability properties, and show that the computing performance is enhanced in comparison to classical implicit methods.

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Characterisation of the Forces and Deformation Experienced by an Adhered Cell

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A critical function of blood cells such as platelets and leukocytes is the ability to adhere to vessel walls. The bonds that form between the cell surface and the vessel wall allow the cell to decelerate from the blood flow and stably attach. Accurate descriptions of forces acting on the bonds between a cell and the vessel wall are essential in determining critical shear rates for cell deformation and detachment. A two-dimensional numerical model, using the boundary element method, has been developed to gain insight into the surface deformation and forces experienced by an adhering, elastic cell in bounded, linear shear flow with negligible inertial effects.

The blood cell model consists of neutrally buoyant, 2D, elastic, constant volume, elliptical capsule of initial aspect ratio a/b tethered to a plane wall in linear shear flow. The capsule is filled with a Newtonian fluid of viscosity μ, and is suspended in an identical fluid. The cell force and deformation are governed by the initial cell aspect ratio a/b and the Capillary number Ca, representing the ratio of viscous forces to elastic forces.

The deformation of a cell is considered for initial aspect ratios of $0.5 \leq a/b \leq 2$. It has been quantitatively established that cells with aspect ratios $a/b > 1$ experience enhanced wall contact, less force and less overall deformation compared to cells of lower aspect ratios. It has also been demonstrated that immediately after adhesion has occurred the cell experiences a maximum force and a maximum overall deformation, during which time enhanced wall contact is observed. The maximum force acting on an adhered cell was found to be a linear function of Ca.

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A mechanical view on Abdominal Aortic Aneurysms

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Abdominal Aortic Aneurysms are a growing dilatation of the Aorta preferentially located at the bifurcation of the iliac. We address the two questions of the localization and growth using a simplified physical experiment in which water [blood] is pumped periodically (amplitude a, frequency f) in an elastic membrane [aorta] (length L, section A_0, elastic celerity c_0) and study the deformation of this membrane while discharging in a rigid tube [iliac] (hydraulic loss K). Local elastic bulges, considered as mechanical analogs of aneurysms, are observed in the experiment when the mean flow-rate $A_0 a^* 2\pi f^*$ exceeds a threshold value, as illustrated in figure 1. This threshold is shown to be independent of the membrane length L, and decreasing with increasing hydraulic resistance K.

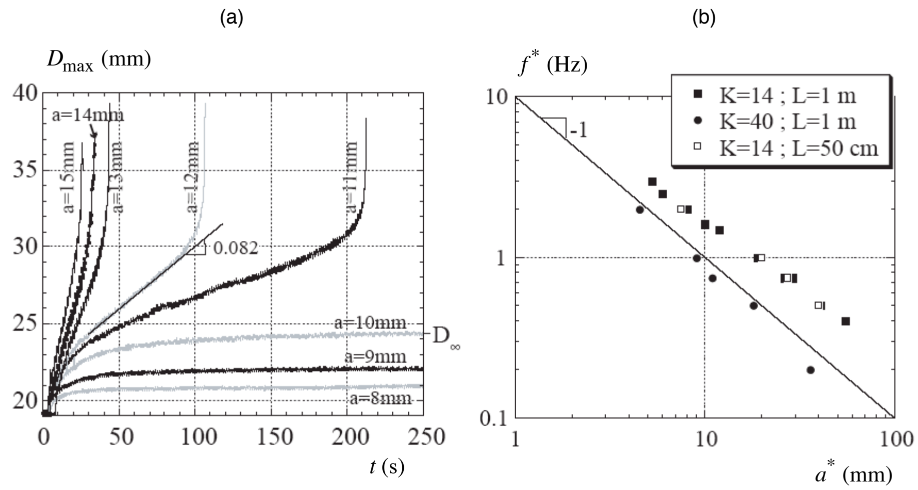

Figure 1: (a) Evolution of the maximum diameter as a function of time for various piston amplitudes a; $K = 40$, $L_0 = 1\text{m}$, $f = 0.75\text{Hz}$. (b) Amplitude and frequency threshold above which a bulges growths without bounds for several hydraulic outlet resistances and lengths.

A lumped Windkessel model for the elastic membrane is then introduced. Besides neglecting spatial inhomogeneities, it is based on a time-averaging procedure smoothing out the fast "cardiac" oscillations. It predicts that aneurysms only develop above a critical flow rate which scales as $A_0 c_0/\sqrt{2K}$, in remarkable agreement with our experiments. The influence of local inhomogeneities (elasticity defects) of the membrane on the threshold for aneurysms is then discussed using a one-dimensional numerical model for the nonlinear waves in the membrane.

Anomalous bubble propagation in elastic tubes

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Airway reopening is an important physiological event, as exemplified by the first breath of an infant that inflates highly collapsed airways by driving a finger of air through its fluid-filled lungs. Whereas fundamental models of airway reopening predict the steady propagation of only one type of bubble with a characteristic rounded tip, our experiments reveal a surprising selection of novel bubbles with counter-intuitive shapes that reopen strongly collapsed, liquid-filled elastic tubes [1].

We characterise these bubbles in terms of their dimensionless speed and the initial level of tube collapse, and find sub-critical exchanges of stability between them [2]. Moreover, our multiple bubbles are associated with a discontinuous relationship between bubble pressure and speed that suggests fundamentally different reopening mechanisms.

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Oscillations and Instability of high-Reynolds-number flow in a collapsible channel

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A by-now standard model for flow in a collapsible tube is that of two-dimensional flow in a parallel-sided channel with a section of one wall replaced by a membrane under constant tension T and at a given external pressure p_{ext}. Far upstream of the collapsible segment there is steady Poiseuille flow at Reynolds number Re Guneratne & Pedley [1] presented a theory for steady flow in such a channel, based on interactive boundary-layer theory. The channel has width a, and the elastic segment has length λa and displacement $O(\epsilon a)$, where $\epsilon = \lambda Re^{-1/3}$. The theory is valid for $1 \ll Re^{1/7} \lesssim \lambda \ll Re$, $p_{ext} - p_o = 0(\epsilon^2 \rho \overline{U}^2)$, $T = O(\epsilon \lambda^2 \rho \overline{U}^2 a)$, where $\overline{U}$ is the average longitudinal velocity and p_o is the internal pressure far upstream. The results showed that for particular values of T and p_{ext}, there may exist 0, 1, 2 or more steady solutions, the number apparently increasing without bound as both T and $p_{ext} - p_o$ tend to zero. In particular, for $p_{ext} - p_o = 0$, there is an infinite number of values of T at which a non-trivial solution exists, as well as the trivial solution.

In this paper we examine the existence of small-amplitude oscillations of real frequency ω about the trivial steady flow, using the linearised time-dependent version of the same theory [2, 3]. We find an apparently infinite number of eigenvalue pairs (T, ω) for which non-trivial solutions exist [4]. We shall also investigate the stability of the trivial steady solution, but this is still work in progress.

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[4] The eigenvalue pairs T, ω (in dimensionless form) are solutions of the equation

$$2\pi T = -36 \int_{-\infty}^{\infty} \frac{2 - (-1)^n e^{ik}}{(n^2\pi^2 - k^2)^2 (6ik)^{1/3}} \, \frac{\mathrm{Ai}'(z)}{\int_z^{\infty} \mathrm{Ai}(s)ds} \, dk,$$

where n is an integer, $z = e^{i\pi/6}\omega/(6k)^{2/3}$, and Ai is the Airy function.

A quasi-one-dimensional model for collapsible channel oscillations

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The motivation of the work is to understand self-excited oscillations that arise whenever a fluid is driven rapidly enough through a flexible tube. These instabilities are believed to have various physiological applications, such as wheezing in airways and Korotkov sound generation during sphygmomanometry.

In the recent numerical simulations by Luo et al. [2008] , a cascade of instabilities was discovered in Reynolds-number-tension parameter space as the wall stiffness was reduced. For a given Re the system at first becomes unstable as the tension is lowered to the critical value. However, as the tension is further decreased the system regains stability before becoming unstable again to a higher mode perturbation.

In the attempt to understand this phenomenon, we consider two-dimensional high Reynolds number laminar flow of a Newtonian incompressible fluid though a collapsible channel. A section of one wall of an otherwise rigid channel is replaced by a membrane with inertia M, under longitudinal tension T, with no bending stiffness and subject to the external pressure P_{ext}. The segments upstream and downstream from the elastic wall are assumed to be infinitely long. Based on the inviscid, large amplitude and long wavelength analysis by Pedley and Stephanoff [1985], the membrane motion is coupled to the time-dependent behaviour of the core flow through a modified KdV equation of the form

$$\sigma A_{xxx} - 12\beta A_t - 36(AF)_x = 6\beta F_t + 36FF_x,$$

where $A(x,t)$ represent a lateral displacement of the core-flow streamlines in the y-direction and $F(x,t)$ defines the shape of the membrane according to the equation

$$P_{ext} - P = MF_{tt} - TF_{xx}, \quad if \quad 0 < x < 1,$$

$$F = 0, \quad elsewhere.$$

Therefore, the spatial dimension of the problem is reduced.

The stability of this system is studied numerically and preliminary results reveal at least mode-one oscillations. The presence of the wall damping is shown to be a necessary condition for the existence of the oscillation for moderate values of wall tension. In the limit of small perturbations, we will be comparing the results with a solution of a corresponding linearized eigenvalue problem, as well as stability theory for higher dimensional models by Davies and Carpenter [1997] and Jensen and Heil [2003] and numerical computations by Luo and Pedley [1998, 2000] and Luo et al. [2008].

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Transit of an elastic capsule through a branching channel

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Considerable research effort has been invested in the study of blood flow in the microcirculation. In contrast to flow in the larger vessels such as the aorta, where the blood may be treated as a homogeneous fluid, inside the capillary network the particulate nature of the blood cannot be overlooked. In the smallest vessels the tube diameter is on the order of the size of a red blood cell, which may need to substantially deform in order to pass through the vessel. Numerous theoretical studies have focused on the flow of deformable cells through narrow tubes and most have tended to focus on the passage of cells through non-dividing tubes (e.g. [2], [3], [4]). The scope of the present work is to model the transit of red blood cells through a branching channel with a view to modelling the passage of red blood cells through capillary bifurcations and determining, for example, the stresses developing in the deforming cell wall and the haematocrit in the daughter vessel beyond the point of branching.

Overlooking the complex geometry encountered *in vivo*, we consider a simplified model in which a single blood cell passes through a two-dimensional branching channel. The blood cell is modelled as a thin-walled elastic fluid-filled capsule carried in a pressure-driven flow. The Reynolds number is assumed to be sufficiently small for the linear equations of Stokes flow to hold. Working within the well-established framework of the boundary-integral method ([1]), the transit velocity, deformation, and stresses prevailing in the cell membrane are computed numerically under a variety of flow conditions. The integral equations are formulated in terms of the unknown membrane velocity, the tractions on the pipe wall, and end-pipe pressures, and are coupled to a constitutive model for the elastic stresses and bending moments inside the cell wall.

Published results are used to validate the model where applicable. The particle motion is examined for various particle sizes and shapes, for different tube fluxes and different fluid viscosities. Emphasis is placed on computing the cell deformation, elastic stresses, and the effect of the particle on the channel pressures.

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Objective

The objective of the conference is to bring together researchers of different communities (applied mathematics, biomechanics, fluid mechanics, physics) working on fundamental problems involving coupling between a fluid and a deformable body. Contributions of work in progress or completed are welcome.

Topics

Experimental, numerical and theoretical presentations will be given on the following topics:

- Aeroelasticity
- Biological internal flows
- Compliant walls
- Elasticity-capillarity coupling
- Flow-induced vibration
- Swimming/Flying
- Swimming of microorganisms
- Wind-plant interaction

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