Nature-inspired passive flow control using various coatings and appendages

by

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"I have lived many lifetimes. First... in Atlantis. Then... on Earth, before the dawn of your civilization. Then I joined the ranks of the Ascended. And finally, I returned to mortal form, to live out my remaining days among the noblemen of Arthur's Court. Or, so I thought. And through all these eons, only one thing has stayed the same: there is never enough time."

Merlin, Archmage of the Round (Stargate SG-1)

Nature-inspired passive flow control using various coatings and appendages

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Abstract

There is a wide variety of tails, fins, scales, riblets and surface coatings, which are used by motile animals in nature. Since organisms currently living on earth have gone through millions of years of evolution, one can expect that their design is optimal for their tasks, including locomotion. However, the exterior of living animals has range of different functions, from camouflage to heat insulation; therefore it is a very challenging task to isolate mechanisms, which are beneficial to reduce the motion resistance of the body.

There are two general categories of mechanisms existing in locomotion and flow control. The first is active flow control, when an organism is actively moving some parts or the whole body (exerts energy) in order to modify the surrounding flow field (for example, flapping bird wings). The second is passive flow control, in which an organism has an appendage or a coating, which is not actively controlled (no energy is spent), but is interacting with surrounding flow in a beneficial way. Our aim is to find novel mechanisms for passive flow control.

We start by looking at a simple model of an appendage (splitter plate) behind a bluff body (circular cylinder). If a recirculation region forms behind the body, already in this simple system there is a symmetry breaking effect for sufficiently short plates, which passively generates turn and drift of the body. We have found that this effect is caused by the pressure forces in the recirculation region, which pushes the plate away from the vertical in a manner similar to how a straight inverted pendulum falls under the influence of gravity. In order to investigate this symmetry breaking, we developed an extension of the immersed boundary projection method, in which the rigid body dynamics and fluid dynamics are coupled implicitly. The method is capable of solving for particle motion in a fluid for very small density ratios. We also explain our findings by a simple yet quantitative reduced-order model and soap-film experiments.

To extend our work, we investigate flow around bodies, which are coated by a porous and elastic material. We have analysed various theoretical approaches to modeling a coating in a continuous manner. We aim to solve the governing equations numerically. We have selected multi-scale expansion approach, of which we present some initial results.

Descriptors: flow control, passive appendage, surface coating, pressure drag, friction drag.

Passiv styrning av strömmning inspirerad av naturen

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Sammanfattning

Många djur använder sig av fjäll, päls, hår eller fjädrar för att öka sin förmåga att förflytta sig i luft eller vatten. Evolutionen har främjat ojämna, sträva eller gropiga ytor, vilka har en tendens att minska det totala motståndet som uppstår när en kropp rör sig i vatten eller luft, jämfört med en helt slät och jämn yta.

Det finns två kategorier av metoder för manipulering av strömning (så kallad flödeskontroll). Den första är en aktiv metod, där organismer aktivt rör hela eller delar av kroppen (förbrukar energi) för att manipulera omgivande strömningsfält. Den andra metoden är passiv, där organismer har utväxter eller ytbeläggningar som de inte är aktivt har kontroll över (ingen energi förbrukas), men som samverkar med omgivande strömningsfält på ett fördelaktigt sätt. Vårt mål är att hitta nya mekanismer för passiv flödeskontroll.

Vi börjar med att studera en enkel modell för hur en utväxt samverkar med en strömmande fluid genom att fästa en platta på en cirkulär cylinder. Om en vak (så-kallad återcirkulationsregion) bildas bakom kroppen, bryts symmetrin i strömningsfältet då plattan är tillräckligt kort. Som en konsekvens av detta roterar kroppen och driver i sidled. Vi visar att detta fenomen orsakas av tryckkrafter i återcirkulationsregionen, som förskjuter plattan från dess vertikala läge. Vi argumenterar att denna mekanism är samma mekanism som får en inverterad pendel att falla under inverkan av gravitation. För att analysera symmetribrytningen, utvecklade vi en numerisk metod (immersed boundary projection method), som implicit kopplar stelkropps- och strömningsdynamik. Med hjälp av denna metod kan vi simulera partiklar i fluider med väldigt låga densitetsskillnader. Våra resultat förklaras även med hjälp av en enkel modell av låg ordning och med hjälp av såphinneexperiment.

Som nästa steg i vårt arbete, ämnar vi att studera strömningen kring kroppar som är belagda av tät, porös och elastisk beläggning. Vi har analyserat möjliga tillvägagångssätt för att modellera beläggningar med kontinuumteori. Vi har valt en metod baserad på en flerskalig expansionsmetod, från vilken vi presenterar våra preliminära resultat.

Deskriptorer: Flödeskontroll, passiva bihang, ytbeläggning, tryckmotstånd, friktionsmotstånd.

Preface

This thesis deals with the development of passive flow control techniques based on mechanisms observed in nature. A short introduction on main ideas and aims, as well as tools employed is presented in the first part. The second part contains three articles. The first paper is published in *Nature Communications*, the second paper will be submitted to *Journal of Computational Physics*, and the third paper is an internal report. The manuscripts are fitted to the present thesis format without changing any of the content. All images acquired externally have been released to public domain by their authors under license **CC0 1.0**.

Paper 1. U. Lācis, N. Brosse, F. Ingremeau, A. Mazzino, F. Lundell, H. Kellay, & S. Bagheri. *Passive appendages generate drift through symmetry breaking.* Nat. Commun. **5**, 2014

Paper 2. U. Lācis, K. Taira, & S. Bagheri. *A stable fluid-structure-interaction solver for low-density rigid particles using the immersed boundary projection method.* To be submitted to J. Comput. Phys., 2014

Paper 3. U. Lācis & S. Bagheri. *A continuous description of porous and elastic media for the simulation of the flow around coated objects.* Internal report, 2015

January 2015, Stockholm
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Division of work between authors

The main advisor for the project is Prof. Shervin Bagheri (SB). Prof. Fredrik Lundell (FL) acts as co-advisor.

Paper 1

The simulation code for two-dimensional case initially developed by SB has been extended by Uğis Lācis (UL) to incorporate rigid-body dynamics. Simulations of freely falling body has been performed by UL. The theoretical model has been created by UL and further developed with feedback from all authors. Nicolas Brosse performed the soap film experiments of fixed cylinder with feedback from FL. Francois Ingremeau and Hamid Kellay performed the soap-film experiments of the free-hanging cylinder. Andrea Mazzino supervised the numerical simulations of the three-dimensional sphere, done by Stefano Olivieri. All authors analyzed data. SB and UL wrote the paper.

Paper 2

The numerical method was extended by UL and the extension was later improved by Kunihiko Taira (KT) to recover positive-definiteness property of all solution steps. Results were obtained and paper was written by UL with feedback from KT and SB.

Paper 3

The existing theories for modeling continuous poro-elastic coating was investigated by UL and discussed with SB. Numerical simulations of micro-scale equations were performed by UL with a feedback from SB.

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Part I - Overview and summary

Part I

Overview and summary

CHAPTER 1

Introduction

Animals currently living on earth have gone though millions of years of evolution. During all these years, the variety and function of those organisms have developed tremendously. Currently there are around 1.5 million species in the animal kingdom of various shapes, covered by all sorts of skins and have wide range of abilities.

Exact mechanisms, which are used by animals for locomotion and flow control, are still actively researched. There are two general categories of such mechanisms. The first and the most common category is active flow control. The main property of an active flow control is that the animal must *spend energy* in order to modify the surrounding flow. The advantage of the active flow control is a relatively simple design, since a force or a motion can be prescribed. A bird is a very common example which uses an active flow control – flapping wings. In Figure 1.1a we show a Scissor-tailed Flycatcher. Also fishes commonly employ active mechanisms (such as bending their whole body) to swim (see Figure 1.1b).

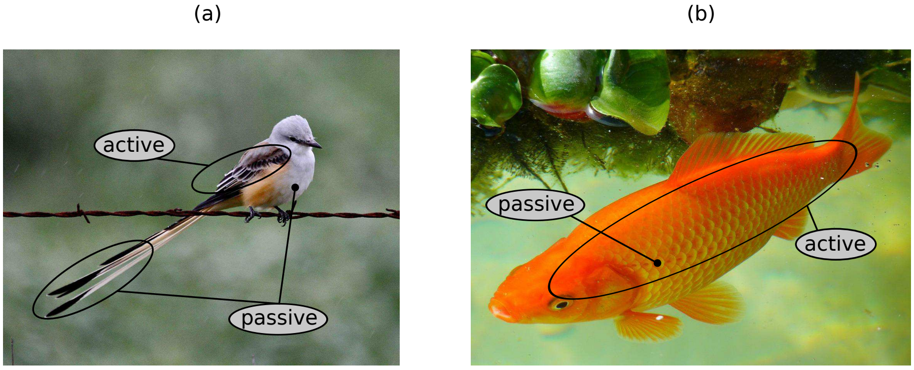

FIGURE 1.1. Examples of two motile organisms, a bird (a, Scissor-tailed Flycatcher) and a fish (b, Goldfish). The bird (a) flaps its wings actively in order to fly, while tail and feathers might passively improve aerodynamical properties. The fish (b) bends its body actively in order to swim, while scales might passively reduce flow resistance.

The second category is passive flow control. The main property of a mechanism within this category is that *energy input is not required* from the organism. Instead, an appendage or a coating is interacting with the flow and forcing is generated in a coupled fluid-structure interaction (FSI). This flow control is often more complex to develop compared to active flow control. The obtained forcing is determined by a complex non-linear FSI instead of being imposed directly using a muscle force or an engineered device (such as plasma actuator). For example, many birds have feathers and tails (Figure 1.1a), which can interact with surrounding flow passively. Also fishes have various fins and scales (Figure 1.1b). Riblets (Lang *et al.* 2011) model scales of sharks and reduce friction drag.

In this thesis we consider passive flow control mechanisms. We believe that there are still unexplored possibilities to learn from nature and come up with a better techniques for reducing motion resistance of man-made transportation utilities, such as cars and planes. Passive control mechanisms are challenging to isolate, because functions of animal skin often includes, but is not limited to, heat insulation, protection from damage, camouflage.

The investigation of passive flow control mechanisms found in nature is multidisciplinary. In order to describe behaviour of surrounding fluid, the knowledge of fluid dynamics must be invoked. To describe tails or feathers of animals, deformation much be characterized by solid mechanics. To capture the properties of the deforming natural bodies, one has to look in biology and find, for example, how the elastic properties of given tissue depend on surrounding conditions. In our work, we focus on fluid mechanics and solid mechanics.

1.1. Fluid mechanics

Figure 1.2. An example of an incompressible fluid flow. Water is flowing from through a narrow passage of a river, during which a very chaotic patterns can be seen.

Fluid mechanics is a discipline, which investigates a fluid flow in a continuous manner. An example of fluid flow is shown in Figure 1.2. A velocity value $\mathbf{u}$ is assigned to a fluid parcel, which is sufficiently large from microscopic point of view, such that movement of individual molecules or atoms is not important, and in the same time sufficiently small from macroscopic point of view, such that the system of interest is composed of infinitely many fluid parcels.

In current work we look at fluids, which are assumed to be incompressible. This assumption holds for most of liquids, and also for gases, in which flow speed is significantly smaller (below 30%) compared to speed of sound. The motion of the fluid is governed by incompressible Navier-Stokes equations

$$\rho \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \boldsymbol{\nabla})\, \mathbf{u} \right] = -\boldsymbol{\nabla} p + \mu \nabla^2 \mathbf{u}, \tag{1.1}$$

$$\boldsymbol{\nabla} \cdot \mathbf{u} = 0, \tag{1.2}$$

$$f\left(\mathbf{u}, p\right)\big|_{\partial\Omega} = \mathbf{g}_{\mathrm{BC}}, \tag{1.3}$$

where ρ is the fluid density, $\mathbf{u}$ is the fluid velocity field, p is the fluid pressure, μ is the dynamic viscosity of the fluid, $f\left(\mathbf{u}, p\right)\big|_{\partial\Omega}$ is a general function of boundary velocity and pressure values and $\mathbf{g}_{\mathrm{BC}}$ is a general boundary condition on a surface of a fluid domain (can be both prescribed velocity or surface stress). It is common to define the dimensionless number called Reynolds number as $Re = \rho U L/\mu$, where L is a characteristic length scale of the system. The Reynolds number characterizes the ratio between inertial and viscous forces in the specific problem.

Navier-Stokes equations are non-linear partial differential equations. Analytic solutions are available only for very limited set of problems, therefore it is more common to conduct numerical (see section 2.1) or experimental (see section 2.2) investigations.

1.2. Solid mechanics

In case of a non-deformable body, the rigid body dynamics is very simple. For any arbitrary body there are 3 degrees of freedom in two dimensions (translation in two directions, rotation around axis orthogonal to two-dimensional plane) and 6 degrees of freedom in tree dimensions (translation in three directions, rotation around three axis). Velocities are assigned to the center of the mass of the body and the motion is governed by the total force on the body. In two-dimensional setting the governing equations (so called Newton's equations) are

$$\frac{d\mathbf{u}_s}{dt} = \frac{1}{\rho V_s} \oint_S \overline{\overline{\boldsymbol{\tau}}} \cdot \hat{n}\; dS + \left(1 - \frac{1}{\rho}\right) g \hat{e}_g, \tag{1.4}$$

$$\frac{d\omega_s}{dt} = \frac{1}{\rho I_s} \oint_S \mathbf{r} \times \left(\overline{\overline{\boldsymbol{\tau}}} \cdot \hat{n}\right)\; dS, \tag{1.5}$$

where $\overline{\overline{\boldsymbol{\tau}}}$ is the fluid stress tensor, $\mathbf{u}_s$ is the translation velocity, ω_s is the angular velocity, $\mathbf{r}$ is the radius from the center of mass to the surface of the body, $V_s = \int dV$ is dimensionless volume, $I_s = \int \mathbf{r}^2\, dV$ is dimensionless moment of inertia, and $\partial\Omega_{fs} = S$ is the solid object surface. Nevertheless, solid bodies are often deformable. A simple example of a deforming solid body is a ruler placed on a table, and bent by forces acting at the end of the ruler and at the center of the ruler (see Figure 1.3).

FIGURE 1.3. An example of a deformed ruler. A force is applied at both ends of the ruler and at center of the ruler (reactive force form table), which causes a bending of the ruler.

The deformation is described in continuous manner using a displacement field $\mathbf{v} = \mathbf{x} - \mathbf{x}_0$ for each solid body element, which is a difference between current position $\mathbf{x}$ and initial (rest) position $\mathbf{x}_0$ in the coordinate system moving together with the center of mass of the body. In the deformed case the limited number of degrees of freedom have been replaced by a continuous field.

The difference of displacement through the body (strain) is translated to stress through a given stress-strain relationship. In current work we look at linear elasticity, i.e., in which the relation between strain and stress is a linear function. The governing equation for deformation of solid body then is

$$\begin{aligned} \rho_s \frac{d^2\mathbf{v}}{dt^2} &= \nabla\cdot \left[\mathbf{C} : \frac{1}{2}\left\{\boldsymbol{\nabla}\mathbf{v} + (\boldsymbol{\nabla}\mathbf{v})^T\right\}\right] + \mathbf{F}, \\ \text{B.C. 1} \;\; \mathbf{F}_b &= \left[\mathbf{C} : \frac{1}{2}\left\{\boldsymbol{\nabla}\mathbf{v} + (\boldsymbol{\nabla}\mathbf{v})^T\right\}\right] \cdot \mathbf{n}, \\ \text{B.C. 2} \;\; \frac{1}{V}\int \mathbf{v}\, dV &= \mathbf{v}_c\,(t)\,, \quad \frac{1}{V}\int \mathbf{r}\times\mathbf{v}\, dV = \theta_c\,(t)\,, \end{aligned} \tag{1.6}$$

where ρ_s is the density of the structure, $\mathbf{C}$ is a forth order tensor, which relates strain and stress of the structure, $\mathbf{F}$ is a body force within the structure, $\mathbf{F}_b$ is the prescribed boundary forcing, $\mathbf{n}$ is the normal vector of the surface, and $\mathbf{v}_c$ and θ_c are prescribed position and turn of the center of mass, necessary boundary condition on displacement field values to complete the formulation.

CHAPTER 2

Physical problem and research methods

In order to assess the effect of an appendage or a coating on the aerodynamic properties of a moving animal, we define two test problems. As the first problem, we consider an animal which has a tail and moves through the fluid (see Figure 2.1a). For the second problem, we consider an animal which is coated with feathers (one example of poro-elastic coatings) and moves through the fluid (see Figure 2.1b). We assume that there is a *drag* wake behind these bodies, which appendage and feathers are exposed to. It would be the case, if animal would be dragged through the fluid, or if the animal produces trust far away from the main body, such that there are vortices forming due to both *thrust* and *drag*.

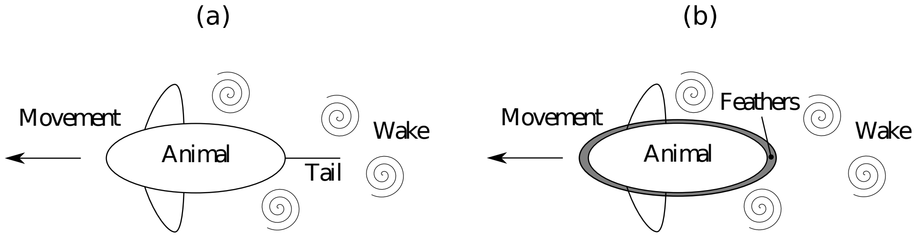

FIGURE 2.1. Schematics of two models. We show model of an animal with a tail (a) and of an animal coated with feathers (b), and their *drag* wakes.

To investigate the first problem, we select a simple model (cylinder with a splitter plate) to represent the animal. We then let the cylinder with the plate fall under the influence of the gravity. Our findings of investigation is published in paper 1. Our initial work towards solving the second problem is explained in paper 3.

In the following sections we give a short overview of research methods we have used in order to investigate the first problem. First, we introduce a numerical simulation technique we have developed to obtain numerical results. Second, we explain the experimental work in order to validate our findings.

2.1. Numerical simulations

It is often convenient to investigate FSI problems using numerical tools. The advantage of numerical simulation is that the flow field is accessible over all simulation domain at once. Another advantage is that changes in system (such as geometry, elastic properties, etc) can be relatively easily imposed. Nevertheless, for complex systems (for example, strong FSI or intensive turbulence) computations can be extremely expensive.

In our work we employ a numerical method to solve rigid body motion in fluid similar to immersed boundary (IB) method, originally developed by Peskin (1972) for describing flow patterns around heart valves. The underlying idea is to discretize Navier-Stokes equations on a regular structured grid, and represent a body of arbitrary geometry on a separate grid (see Figure 2.2).

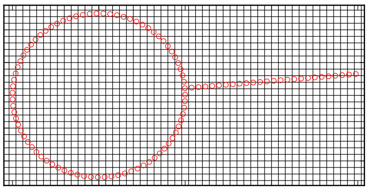

FIGURE 2.2. Example of cylinder with splitter plate within a IB framework, body represented using Lagrangian grid (red circles) and fluid represented using structured Eulerian grid (black lines).

The interaction between Lagrangian grid and Eulerian grid is imposed by interpolation and spreading (regularization) operators. The velocity of the fluid $\mathbf{u}(\mathbf{r})$ is interpolated from Eulerian grid to the Lagrangian grid, while the forcing from the solid body $\mathbf{F}(\mathcal{L})$ is spread from Lagrangian to Eulerian grid

$$\mathbf{U}(\mathcal{L}) = \int_{\Omega} \mathbf{u}(\mathbf{r})\delta(\mathbf{r}-\mathcal{L})\ dV, \tag{2.1}$$

$$\mathbf{f}(\mathbf{r}) = \int_{S} \mathbf{F}(\mathcal{L})\delta(\mathcal{L}-\mathbf{r})\ dS, \tag{2.2}$$

where $\mathbf{r}$ is the coordinate vector to Eulerian grid, $\mathcal{L}$ is the coordinate vector to Lagrangian grid, $\mathbf{U}(\mathcal{L})$ is the interpolated velocity on Lagrangian points, $\mathbf{f}(\mathbf{r})$ is the regularized force density on Eulerian points and $\delta(\mathbf{r}-\mathcal{L})$ is the Dirac delta function. We carry out simulations for two-dimensional domain. For more details see paper 2.

2.2. Soap-film experiments

Even if a numerical simulation has been performed before, an experimental confirmation provides a better understanding of how a real life system would behave. In some cases it is preferable to conduct experiments. For example, it is computationally very expensive to obtain a solution of fully resolved turbulent flow for high Reynolds number; but the flow can be investigated experimentally relatively easy. If the measurement resolution if acceptable for a task in mind, then experimental investigation can be preferable.

For current work, we select a soap-film experiment. Since the work by Kellay *et al.* (1995*a*) on turbulence in a soap-film, this experimental method have been developed tremendously and has found applications in FSI field as well. The soap-film experiment is widely known as a good approximation to a two-dimensional experiment and as such it is very suitable to compare with our two-dimensional numerical simulations. A schematic of a soap-film apparatus is shown in Figure 2.3a. We have built our own apparatus with feedback from Kellay, the pictures are shown in Figure 2.3b,c.

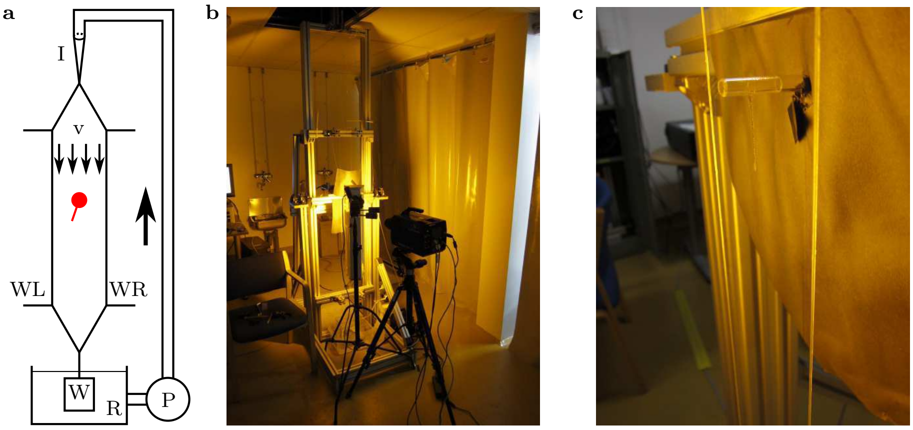

FIGURE 2.3. Schematic of a soap-film experimental facility (a). Overview of experimenatl facility in Stockholm (b), and zoomed view of a cylinder with a filament immersed inside the soap-film (c).

The soap solution is driven from the reservoir by a constant-flux pump P (Figure 2.3a) to the top. Then soap solution falls in between two nylon wires under the influence of gravity and forms a thin soap-film. The soap-film flows around an object placed in the test section (fixed or free to rotate), thus forming a wake behind the body. The thickness variations of the soap-film serve as proxy of the flow field. We make measurements of flow field using a high-speed camera. We observe global characteristics of the body, such as turn angle.

In addition to soap-film experiments done in Stockholm, another set of runs were performed in Bordeaux. There we hanged the body in a loose pendulum, in order to observe not only turn of the body, but to also detect a side force, if there is any. For more details on soap-film experiments, see Methods section in paper 1.

CHAPTER 3

Summary of the papers

Paper 1

Passive appendages generate drift through symmetry breaking

In this paper, we investigate a very simple model of an appendage behind an animal – splitter plate behind a circular cylinder. We show that although generally a recirculation region behind a body is not desirable and increases drag, some of that lost energy can be recovered using a symmetry breaking. We show that a short splitter plate in the wake becomes unstable in a similar manner as inverted pendulum becomes unstable under the influence of the gravity, thus we denote it as inverted-pendulum-like (IPL) instability. Although this effect has been observed previously both for rigid and elastic appendages, the precise mechanism and consequences remain unknown. We demonstrate the turn and drift both experimentally (using soap-film experiments at Reynolds number around tens of thousands) and numerically (Reynolds number around hundred). Then we unravel the mechanism responsible for the symmetry breaking using a very simple, yet quantitative model. Then we demonstrate that the IPL instability is relevant also for elastic appendages (which are more common in nature compared to rigid appendages) and in three dimensions. We conclude that the mechanism we have demonstrated could possibly be exploited by organisms in nature and suggest other researchers to look for them.

Paper 2

A stable fluid-structure-interaction solver for low-density rigid particles using the immersed boundary projection method

In this paper, we describe the numerical method, which we developed while working on the paper 1. We use an immersed boundary projection method as basis for our fluid solver and couple it with rigid body dynamics. We have found that explicit coupling, which is commonly used to find solution of cylindrical and spherical particle motion in fluid, becomes unstable for bodies with non-dimensional density close to unity, if splitter plate is added behind the body. In order to obtain small Reynolds numbers in the gravity of earth, we devised an implicit coupling scheme. We show in the paper that the implicit scheme is stable for very light particles. We also show that the extension we have developed does not increase the computational cost and retains the accuracy of the original method.

Paper 3

A continuous description of porous and elastic media for the simulation of the flow around coated objects

In this paper, we describe the basics of three alternative approaches to model poro-elastic materials with continuum equations. The first approach is mixture theory, the second approach is multiple scale expansion, and the third approach is method of volume averaging. The mixture theory is found to be the simplest out of investigated ones, however it includes empirical models of interaction between "mixed phases". The multiple scale expansion and volume averaging approaches are more rigorous; these theories attack two different ends of the problem. In the multiple scale expansion, the scales of a problem are identified at the very beginning and the expansion is done on original equations. The resulting formulation is averaged over a characteristic volume. On the other hand, in volume averaging approach the original equations are averaged over the characteristic volume beforehand. Scales of resulting equations are analysed afterwards in order to simplify the problem. We select the multiple scale expansion because of a simpler final formulation for the description of poro-elastic material. And finally, we present some initial results from the microscale problem of the multi-scale expansion.

CHAPTER 4

Conclusions and outlook

In current work we have considered a single appendage behind a bluff body and its effect on aerodynamic properties. We have looked both at solid and elastic appendages, and also both at two-dimensional and three-dimensional configurations and observed an inverted-pendulum-like (IPL) symmetry breaking. We have investigated in more details the two-dimensional rigid case, which we have described numerically, experimentally and also theoretically. We have determined that IPL is not an elastic instability, but a basic FSI instability. We have concluded that the necessary conditions for the IPL instability to happen are separated flow and sufficiently short appendage.

We have also expanded the immersed boundary (IB) projection method to include an implicit coupling with Newton's equations of motion. Our method has allowed us to investigate freely falling bodies with a non-dimensional densities close to unity, which corresponds to Reynolds number around hundred in gravitational field of earth. We have shown that method retains accuracy and efficiency of the original IB projection method. We have also noted, that the approach can be useful for coupling the fluid solver to more complex equations as well.

In the future it would be interesting to investigate the contribution of elasticity for the behaviour of a single appendage. We aim to research a collective behaviour of many filaments or different structures, which form a poro-elastic media. We want to understand the existing theoretical framework in modelling such materials. We plan to advance it to be able to perform numerical simulations of models resembling real organisms.

Acknowledgements

I would like to express my gratitude to Prof. Shervin Bagheri for his accepting me for this PhD project and guiding through all the hard work. I also want to thank Prof. Fredrik Lundell for lessons on planning and endless enthusiasm and broad view on research problems, which can be exhaustive and complicated in their details.

I appreciate the fruitful collaboration I had with researchers both in France and Italy, and also here in Stockholm during the work on my first paper. I thank Nicolas Brosse for his patience and his good work on setting up and carrying out soap-film experiments.

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