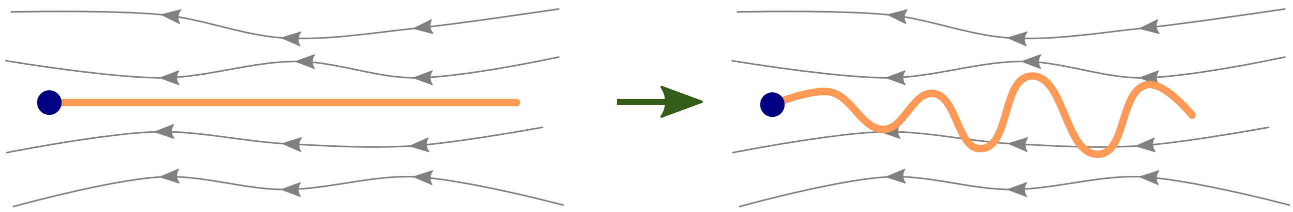
Dynamic deformation of elastic filaments in viscous fluids

Description for the general public

The project focuses on the motion of long and elastic filaments in a viscous fluid. This is motivated by microscopic soft matter systems, in which elongated fibre-like structures are immersed in a fluidic environment. Examples of such structures include the helical flagella of bacteria, cilia and flagella of eukaryotic microorganisms, elongated rod-shaped viruses, polymeric fibres, protein structures and strands of DNA. All of these structures exhibit elastic properties, which means they can be deformed (twisted or bent) and that this deformation induces elastic stresses which resist the motion. On the other hand, when moving in a viscous fluid they experience hydrodynamic stresses due to the fluid drag forces.

Flow of liquids in microscale is very different to our everyday experience. For a given flow, the relative importance of inertial and viscous effects in the fluid is measured by the Reynolds number. The Reynolds number is very small when the moving objects are small and move slowly in a fluid. Likewise, it can be made small even for larger and faster objects, provided that a fluid of suitably high viscosity is used. Due to a mathematical analogy, flows with similar Reynolds numbers have a similar character. Thus, microscale objects in fluids like water experience the same kind of dynamics we would observe in honey, glycerine, or another very viscous fluid.

The aim of this project is to understand and explore what happens when both elasticity and a very viscous fluid are shaping the motion. When elongated structures are not stiff enough to withstand the large stresses exerted by the surrounding fluid, which may be caused by an external flow, they might deform as in the sketch below. Their bent shape will be more favourable energetically, but the way the shape is obtained and the deformation grows remains largely unexplored. This phenomenon, known as the buckling instability, will be in the focus of the project.



Dynamic buckling occurs when the filaments are exposed to flow or move through a viscous fluid and the hydrodynamic stresses cannot be sustained by compressive elastic stresses in the fibre, leading to a time-dependent deformation (as in the sketch). By combining the elements of theoretical analysis, development and application of numerical predictive tools, and experimental verification, we hope to reveal and quantify the mechanisms and effects of the dynamical buckling instability and identify the key properties of the system that determine the motion.

To fill this gap, we will construct a suitable theoretical description accounting for the elastic properties of the fibres, and for their hydrodynamic interactions with the surrounding fluid. Then, we will implement it, creating a robust and flexible tool for numerical simulations of elongated filaments under general flow conditions.

This tool will be used in two practical experimental settings. Firstly, a macroscale model for a long fibre will be investigated, in which a filament will be pushed into a container filled with a very viscous fluid. The deformation of an initially straight fibre will be recorded and analysed in comparison with the developed simulations. This should give us an insight into the dynamics of buckling under the fully controlled motion. Secondly, a microfluidic system will be developed to study the dynamic buckling in microscopic filaments exposed to a controlled external flow. This will allow to analyse a different aspect of the instability, namely flow-driven deformation.

The project is expected to contribute to the understanding of small-scale fluid-structure interactions. Contrary to static buckling experiments, known e.g. in construction engineering, the mechanism of growth of the dynamic buckling instability has not yet been explored in detail and the role of the elastic parameters of the fibre and properties of the flow have not been identified. It is envisioned that the outcome of this project will be helpful in the design of microfluidic systems involving fibrous structures, and will facilitate interpretation of biophysical experiments with swimming cells and microorganisms involving the motion of flagella and cilia, which form a robust and omnipresent propulsion mechanism. Their dynamics are hugely shaped by the competing elastic and hydrodynamics effects, and the predictive tools produced within this project could prospectively be used to elucidate and explore their complex motion.