Hydrodynamics of flagellar propulsion

Prabhakar Ranganathan

Ph.D. position available

This project is a collaboration between Prabhakar Ranganathan, and James Friend and Leslie Yeo of the Micro/Nanophysics Research Laboratory (MNRL). We are looking for somebody with a H1-Equivalent graduate degree in either engineering, physics or mathematics to take on the challenge of setting up computer simulations to study an important problem that has potential applications in nanotechnology, microfluidics, medicine and biology. A PhD in this multidisciplinary project can be the stepping stone to an exciting academic or research career in a number of fields: computer simulations, nanotechnology, mechanical/ chemical/ materials engineering, microfluidics, biophysics etc. Scholarships are available from Monash University for applicants with a strong (*i.e.* H1E) academic background.

Aims and background

Many microorganisms like bacteria, microalgae, and sperm propel themselves in a fluid environment by means of thin filamentous extracellular projections called *flagella*. This Project aims to take advantage of the recent development of a novel piezoelectric ultrasonic micromotor at the MNRL, which can be used in micron-sized robots—**microbots**—to drive artificial flagella. Using these microbots, it is possible to perform controlled experiments to study the hydrodynamics of flagellar propulsion at the micro-scale. The broad goals of this Project are to combine such experiments with computer simulations to a) understand how the coupling of the elasticity of a flagellar filament with hydrodynamics influences the propulsion of a microbot, and b) to use this improved understanding to optimize the shape, size and material properties of an artificial flagellum and thus create a hydrodynamically efficient prototype of a swimming microbot.

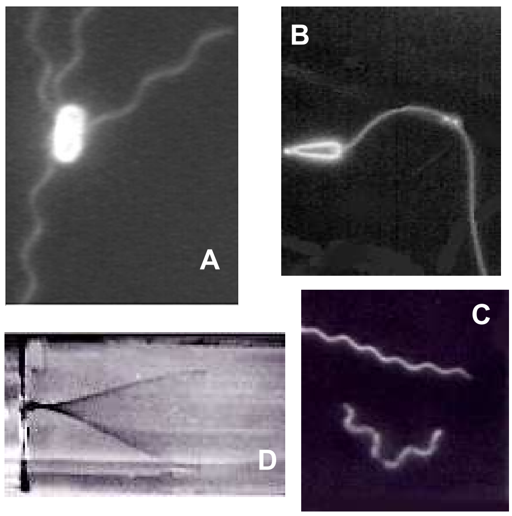

Figure 1: *The basic kinds of flagella: (A) rigid, chiral (helical), passive flagella in an* E. coli *cell (B) elastic, achiral, active flagellum in a sea-urchin sperm cell; (C) elastic, chiral (helical), active* Spiroplasma *cell body; (D) elastic, achiral, passive artificial filament impeller in preliminary experiments. We propose to study the propulsive characteristics of passive elastic flagella, and optimize their design for use in swimming microbots.)*

The essential difference between the hydrodynamics of propulsion at large (e.g. ships and planes) and small (e.g. microbial) length scales is that motion at the microscale takes place in the near absence of inertia, and the net force on any body, or any portion of it, is always close to zero. For organisms or machines that seek to achieve propulsion by rotating or waving propellers fixed to one of their ends, the absence of inertia has important consequences. Although these general principles are well known, there is no consensus on which designs are efficient, nor studies comparing different types of flagellar propellers for their propulsion characteristics.

In nature, bacterial flagella are normally stiff left-handed helices. The hydrodynamics of propulsion by stiff chiral flagella in the absence of boundaries has been widely studied both theoretically and experimentally. Most other motile organisms, however, appear to prefer elastic flagella for propulsion. Microbial elastic flagella also tend to be "active" in the sense that the flagellum is deformed in a controlled manner by the action of internal agents such as kinase protein motors. However, it is perhaps safe to say that the design and fabrication of artificial, internally-driven microscopic active elastic filaments for use in self-contained propulsion systems are beyond the reach of current technology.

Passive elastic filaments, on the other hand, can be externally driven—for example, by a motor at one end—and are quite easy to handle experimentally. Nevertheless, to the best of our knowledge, there are no instances of passive elastic (chiral or achiral) filaments being used as propellers in the microbial world. Such flagella are also the least studied in the available literature, and this may be because their analysis is much more involved than either of passive but rigid (and chiral) flagella, or active elastic flagella which deform in a predetermined manner. Recent simulations show that the filament undergoes unexpected transitions in shape as the imposed torque is increased, and these transitions alter the propulsion developed considerably. Preliminary experiments with unbent filaments at the MNRL also show evidence of such transitions in shape.

Significance and innovation

Perhaps the most far-reaching impact of the investigations proposed in this Project will be the development of a well-tested and optimized propulsion system for swimming microbots that will one day become indispensable tools in minimally invasive surgery, which seeks to reduce the shock to the body caused by major surgery. But the dream of a microrobot operating *in vivo* and remotely controlled by a surgeon, has remained unrealized, hampered crucially by the lack of a viable artificial propulsion system, comparable in size to some of the smaller vessels in the human vasculature. Overcoming this barrier requires breakthroughs on the two basic components of a microscopic propulsion system: the actuator, and the propeller. Among these, the development of the micromotors is already advanced. The innovative combination of experiments with the micromotor and artificial flagella on the one hand, and advanced computer simulations on the other, will deliver a microscopic propulsion system, enabling the further development of frontier technologies in microrobotic surgery. Such a development will certainly transform surgical practise and health-care not only in Australia but all over the world.

At a more fundamental level, the simulations and experiments in this study will throw light on several unresolved questions regarding flagellar propulsion. For instance, why is it that passive elastic propellers are excluded out of the microbial world, although structurally they appear to be the simplest alternatives for propellers? Does the existence of shape transitions render such propellers unreliable, and has natural selection therefore resulted in the overwhelming predominance of other kinds of propellers? In addition to questions regarding propulsion itself, the motion generated by the propellers is also of interest, both from the fundamental as well as the applied points of view. In particular, this study will also explore what strategies a microswimmer may employ to use the propulsion system to steer clear of collision with surfaces and other particles.

Interested candidates can mail prabhakar.ranganathan@eng.monash.edu.au, james.friend@eng.monash.edu.au or leslie.yeo@eng.monash.edu.au for additional information.