M2 INTERNSHIP
ORIGAMI: Designing the elastic response of an object in a fluid

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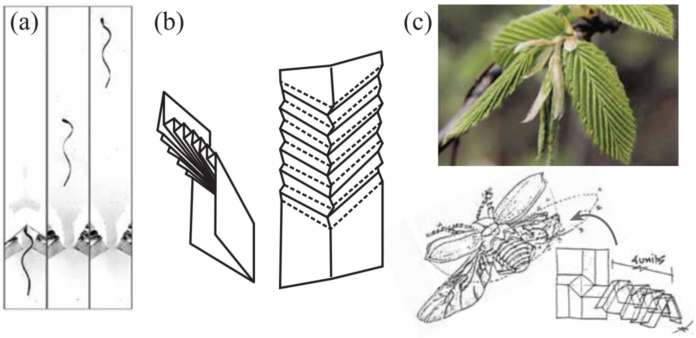

Figure 1: (a) Simple elastic swimmer propelling at the surface of a water tank through body undulations [1]. (b) Example of origami that undergo large shape changes while folding along a single degree of freedom. (c) Deployment mechanisms and folding patterns of a hornbeam leaf and of the wing of a beetle [2].

There is a long-standing interest in the use of flexible materials for robotic propulsion, or energy harvesting from flows [3]. For example, a mere elastic filament actuated at one of its extremities can reproduce the undulating motion of an eel (see Fig.1a), and replace the complex action of coordinated fish muscles [1]. However, the structure has to deform in an appropriate way, that is specific to its function. It is thus important to understand the mechanisms governing the elastic response of an object under fluid loading, and to find ways to control it. Here, we will explore an unconventional route to tailor those deformations, making use of the unique properties of origamis.

Origami is the science of sheets folded along creases. The geometry of the folds conditions the way the structure deforms, allowing only for certain motion while being rigid to other modes of deformation (see Fig.1b). Such foldable structures are commonly used in nature, for example in the opening of buds or the deployement of insect wings (Fig.1c) [2]. Folding patterns impart a form of feedback and intelligence to the object, enabling a mechanical coupling between an opening and extension motion for example (Fig.1b-c). The resulting mechanical properties are likely to improve the wind resistance of plants, or to optimize flight performances of an insect by allowing for the wings to modify their shape in the ascending and descending phase of the flapping motion.

In this internship, we will study those biomechanical mechanisms on model geometries of origami in controlled flows, with potential applications in biomimetic engineering. Origami with faces of varying flexibility and deformable folds will be constructed from elastomer or polymer sheets through laser cutting techniques [4]. Their mechanical response in a controlled flow will be characterized experimentally, and further modeled theoretically. Practical applications can also be implemented, using for example the geometry of Fig.1b for propulsion based on drag (like the paddling of a duck), that alternates strokes that push fluid and restoring stroke where drag has to be reduced.

[1] Ramananarivo S., Godoy-Diana R., & Thiria B. (2013). Passive elastic mechanism to mimic fish-muscle action in anguilliform swimming. *Journal of The Royal Society Interface*, 10(88), 20130667.

[2] Kresling B. (2000). Coupled mechanisms in biological deployable structures. *In IUTAM-IASS Symposium on Deployable Structures : Theory and Applications*, pages 229-238. Springer.

[3] Antoine G. O., and de Langre E., and Michelin S. (2016). Optimal energy harvesting from vortex-induced vibrations of cables. *Proc. R. Soc. A*, 472(2195), 20160583.

[4] Overvelde J. T. B. et al (2016). A three-dimensional actuated origami-inspired transformable metamaterial with multiple degrees of freedom. *Nature communications*, 7, 10929.