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EDITORIAL

Special issue: bioinspired fluid-structure interaction

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Abstract
Fluid-structure interaction (FSI) studies the interaction between fluid and solid objects. It helps understand how fluid motion affects solid objects and vice versa. FSI research is important in engineering applications such as aerodynamics, hydrodynamics, and structural analysis. It has been used to design efficient systems such as ships, aircraft, and buildings. FSI in biological systems has gained interest in recent years for understanding how organisms interact with their fluidic environment. Our special issue features papers on various biological and bio-inspired FSI problems. Papers in this special issue cover topics ranging from flow physics to optimization and diagonistics. These papers offer new insights into natural systems and inspire the development of new technologies based on natural principles.

1. Introduction

Fluid–structure interaction (FSI) is a field of science that studies the interactions between fluid and solid objects. It helps us to understand how the motion of a fluid affects the solid objects, and how the motion of the solid objects affects the fluid. From the engineering point of view, FSI was formalized as a subject area following the study of flow-induced vibrations in the early 20th century [1], although much older examples of engineered objects like the Aeolian harp can be found [2]. FSI research has become a cornerstone in many different engineering applications such as aerodynamics, hydrodynamics, and structural analysis, and is certainly important to design efficient systems such as ships, aircraft, and even buildings. Therefore, research in FSI has been used to design efficient systems such as ships, aircraft, and even buildings.

In recent years, there has been an increased interest in studying FSI in biological systems due to its importance for understanding how organisms interact with their fluidic environment. For example, fish swimming relies heavily on using surrounding water to propel themselves forward while also controlling their skin surface and body shape to reduce drag forces. Similarly, internal circulatory systems in biological systems rely heavily upon pressure gradients within vessels that allow blood cells and other materials to be transported around our bodies efficiently without too much energy being wasted by turbulence or friction losses at boundaries. We could continue with a long list of examples that go beyond the aforementioned broad topics of biolocomotion and internal circulatory flows: collective dynamics, sensory-motor systems, canopy flows, energy harvesting, etc.

Overall, it can be seen that FSI plays an important role not only for modern engineering applications but also for fluids outside and inside living organisms where efficient movement or transport in fluidic environments are essential. In this special issue, we have gathered a collection of papers that investigate a wide variety of such biological or bio-inspired FSI problems. The collection brings new insights into how nature harnesses these complex phenomena, allowing us to better understand how these natural systems work and serving as inspiration to develop new technologies based on natural principles.

2. Flapping systems, swimming and flying

2.1. Foils and flexibility
The wake of a flapping foil is the basic model representing the propulsive mechanism of swimming and flying animals that use wings, fins, and body oscillations to drive their locomotion. The reverse Bénard-von Kármán vortex street is one of the landmark features of such wakes, since it is associated

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with the onset of thrust generation. The vortex shedding frequency is clocked by the flapping motion but, in a realistic model the force production dynamics is intimately linked to the elastic response of the flapping structure. D'Adamo *et al* [3] show, using a wind tunnel experiment and hydrodynamic stability analysis, that thrust peaks occur when the wake resonant frequency is tuned with the foil elastic dynamics. Han *et al* [4] show that non-uniformly flexible foils can outperform their rigid and uniformly flexible counterparts, providing guidance for the development of underwater vehicles using simple purely pitching bio-inspired propulsive drives. Paniccia *et al* [5] compute the recoil reaction during flapping and the locomotion speed of a fish-like body using a simple impulse model able to highlight the added mass and the released vorticity contributions. Their impulse model, linear in both potential and vortical contributions, allows one to understand the capability of the potential terms to attenuate the recoil reaction continuously forced by the vortex shedding which is directly related to the wasted energy.

2.2. Wings

Flying insects can perform robust flapping-wing dynamics under various environments while minimizing the high energetic cost by using elastic flight muscles and motors. Cai *et al* [6] propose a fluid-structure interaction model that couples unsteady flapping aerodynamics and elastic wing-hinge dynamics to determine passive and active mechanisms in bumblebee hovering. Their results show that a strategy of active-controlled stroke, passive-controlled wing pitch and deviation enables an optimal elastic storage. The flapping-wing dynamics is capable of producing aerodynamic force while achieving high power efficiency over a broad range of wing-hinge stiffness. Gehrke *et al* [7] introduce a novel design for a bio-inspired membrane wing and investigate its FSIs in a flapping experiment. The membrane wing can passively camber, and its leading and trailing edges rotate with respect to the stroke plane. They find optimal combinations of the membrane properties and flapping kinematics that out-perform their rigid counterparts both in terms of increased stroke-average lift and efficiency. The combined effects of variable stiffness and angle of attack variation, the enhanced aerodynamic performance of membrane wings and has the potential to improve control capabilities of micro air vehicles. Diaz-Arriba *et al* [8] examine the applicability and accuracy of high-fidelity experimental and numerical approaches in the analysis of three-dimensional flapping wings in hovering flight. They show that the time-averaged lift increases with frequency ratio, up to a certain limit that depends on mass ratio. Also, they conclude that wings with dominant spanwise bending can be beneficial to aerodynamic performance when operating under hovering flight conditions.

2.3. Interactions

Beyond the problem of flapping-based locomotion of an agent in a homogeneous environment, a few papers in this Special Issue examine the situation of moving in a more complex environment, such as the perturbed environment produced by a neighbor, or in intrinsically non-homogeneous fluid. Zhu *et al* [9] present a numerical study on the collective motion of two fish-like swimmers in fluids. They use a hybrid method that couples CFD and machine learning, where the two swimmers are trained to learn their control strategies using the deep reinforcement learning method. They show that different stable formations can be obtained, depending on the initial relative positions of the swimmers. The cruising speeds and energy efficiency of the different formations are compared to those of the isolated swimmer. Kandel and Deng [10] study numerically the locomotion of a pitching foil in both homogeneous and stratified fluid flows. They show that the stratification modifies the dynamics of the pitching foil in both its wake structure and the drag/thrust force, as well as its propulsive performance. They categorize the effects of stratification on flapping performance or propulsive efficiency according to the internal Froude number, which measures the importance of inertial forces versus the gravitational restoring force. Finally, in an archetypal example of locomotion through a free surface, Bergmann [11] quantifies, using a numerical model that relies on the Navier–Stokes equations, the large propulsive forces needed to enable the jump of a self-propelled dolphin out of water.

2.4. Energy harvesting and flow control

The arrangement of leaves and twigs on foliage creates a complex interacting environment that promotes certain dynamic fluttering modes. While enabling a large amplitude response for reduced flow speeds is advantageous in emerging fields such as energy harvesting, still, little is known about the consequence of such interactions. Ojo *et al* [12] numerically study the canonical bio-inspired problem of the flow-structural interaction of a 2D inverted flag behind a cylindrical bluff body, mimicking a leaf behind a tree branch, to investigate its distinct fluttering regimes. The flag's piezoelectric power harvesting capability is investigated numerically and experimentally for varying geometrical and electrical parameters associated with two conditions that depend on the distance between the cylinder and flag. Carleton *et al* [13] present a method based on FSIs to enforce the trajectory of a passive double pendulum that represents human thigh and shank segments in a walking gait. The interaction between the fluid and the structure comes from a hydrofoil attached to the double pendulum and interacting with the vortices that are shed from a cylinder placed upstream. By comparing the joint positions of the double pendulum with those of human hip, knee and ankle joint positions during walking, they show how the system is able to generate a human walking gait cycle on the double pendulum only using the interactions between the vortices and the hydrofoil.

3. Non-locomotive fluid-structure interaction

In this special issue, we invited papers on FSI inspired by small animals, FSI in plant systems, and wave-fluid interactions. The papers showed the latest advances and developments in the field, including new materials, methods and theoretical approaches inspired by biological FSI.

3.1. Small scale fluid-structure interaction

Bhattacharjee *et al* [14] explore the morphological adaptability and locomotive dynamics of a bacteria-inspired soft robot in highly viscous fluids. Using simple geometrical asymmetry, the rod-like soft robot is able to propel itself at low Reynolds numbers. Ko *et al* [15] find that the ant raft elongates from circular to more streamlined shapes and doubles in aspect ratio before contracting back into smaller circular shapes as it enters dormancy. The elongation observed is associated with a 48% drag reduction. Fluid-structure interaction and agent-based simulations on smooth rafts provide some insight into how the raft reconfigures to generate the elongated shape observed. Claverie *et al* [16] show that increased oscillation frequency of a simplified insect antenna model would translate to an increase in odorant capture. The results showed that increasing the antennal oscillating frequency did indeed increase odorant capture rate, by up to 200%, but only up to a critical frequency.

3.2. Plant-inspired fluid-structure interaction

Tadrist *et al* [17] explore the mechanics of a cellular material inspired by the pulvini of the Mimosa pudica plant, which rapidly folds its leaves when touched. The results show that reversible buckling-induced motion may occur depending on the pressurization pattern and magnitude. This research could have applications in the development of soft robots and other flexible devices that mimic plant movements. Louf and Alexander [18] decompose plant responses into different blocks that can be modeled independently and then combined for a more holistic view. A promising approach is to design plant-inspired soft devices that leverage poroelastic principles to sense, manipulate flow, and generate motion. By studying these processes, researchers hope to gain insight into how plants function and utilize these principles in the design of new soft devices. Godinez *et al* [19] report on the flow fields inside and outside a bio-inspired snapping plunger, highlighting the dynamic-coupling between the two processes. The external flow field is characterized by a strong jet and a vortex ring, while the internal flow field produces complex patterns of cavitating structures. The cavitation cycle is described by the Rayleigh-Plesset model, and the fluctuations of velocity are used to characterize the coupling of both fields.

3.3. Wave-fluid interactions

Rhee *et al* [20] develop a self-propelling robotic device called the SurferBot inspired by the honeybee's survival mechanism. This centimeter-scale device uses wave-fluid interactions similar to those used by the honeybee to achieve rectilinear motion on a fluid surface, reaching speeds of up to centimeters per second. The SurferBot could be used to explore fundamental aspects of active and driven particles at fluid interfaces, as well as in robotics and fluid mechanics pedagogy. Wolf *et al* [21] explore the concept of peristaltic fluid pumping through a periodic contraction wave in a vessel fitted with one-way elastic valves. The spacing of these valves relative to the contraction wavelength is found to play a critical role in efficient pumping. These findings contribute to understanding lymphatic system pumping features and offer insight into designing biomimetic pumping devices. Alviso *et al* [22] examine the two-dimensional flow in a straight channel with rigid walls and elastic supports as a simple model of a generic physiological system (e.g. cardiovascular or respiratory) in which fluid-structure interaction produces large deformation of the wall. They show that self-sustained oscillations are observed at frequencies close to the natural frequency of the system. The predictions of their analytical model for the pressure in the channel is in very good agreement with experimental measurements.

3.4. Vortex-fluid interactions

Scott and Hauert [23] develop sensors for underwater robots inspired by how fish use their lateral line system to sense their surroundings, even in turbulent environments. The importance of design elements used is demonstrated, with a minimum 20% reduction in residual error over sensors lacking these elements. These results are an important step in providing alternate methods of control in underwater vehicles that are simultaneously inexpensive and simple to manufacture. Galler and Rival [24] develop a passive sensor for large-scale flow tracking measurements, inspired by the transport mechanism of plant seeds. The sensor is evaluated using a spherical sensor platform equipped with an IMU and magnetometer subjected to two canonical test cases. The results demonstrate that inertial IMU-based flow sensors are viable for Lagrangian tracking at large atmospheric scales and within highly-transient environments when coupled with a robust dynamic model for inertial correction.

4. Concluding remarks

It was our great pleasure to read all the interesting works submitted to this special issue. The enthusiastic response to the call attests that the field of bioinspired fluid-structure interactions is vibrating with new ideas and holds great promise for the future. Scientists are developing new designs and technologies that increase efficiency and functionality by studying how biological organisms interact with their fluid environments. Besides developing systems and structures that can adapt to changing fluid conditions, with properties inspired by biological organisms, these bio-inspired systems are already improving our understanding of the underlying physical principles that govern fluid-structure interactions, and also giving valuable new insights to biologists.

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