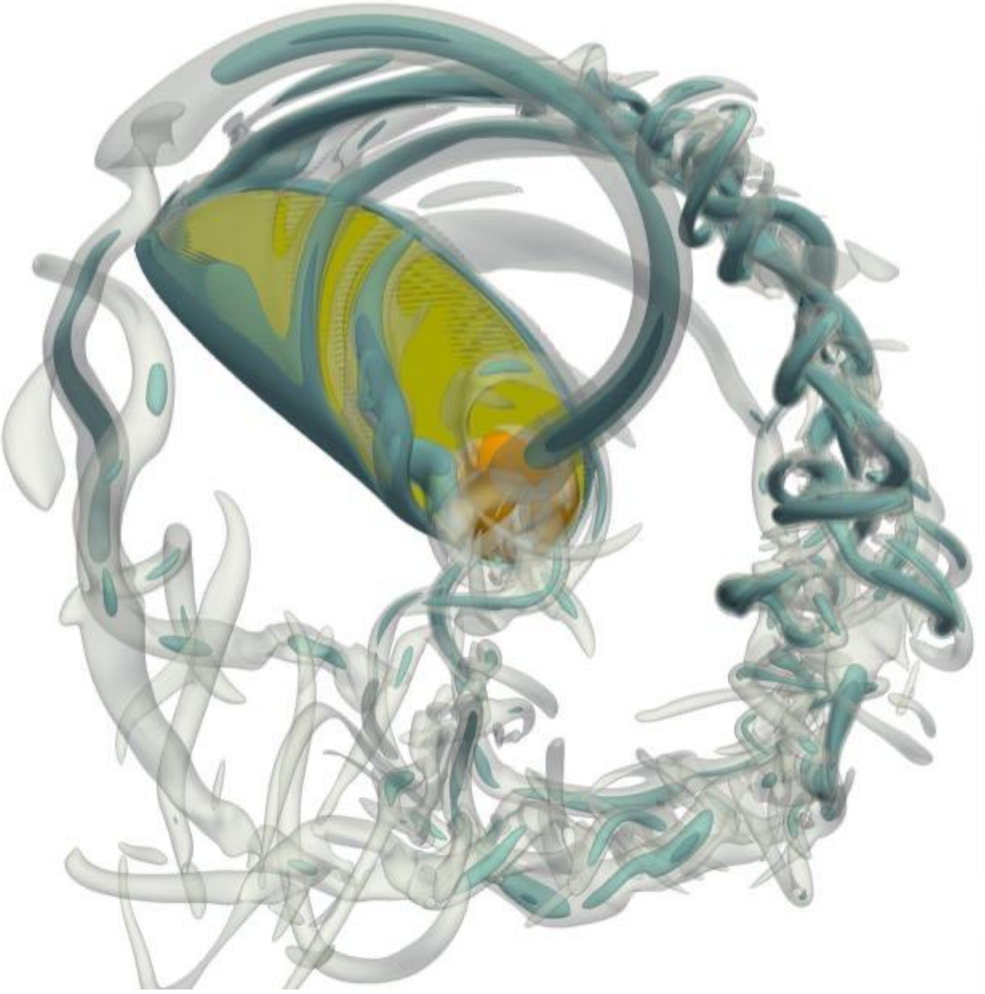
EUROMECH 654

Bio-inspired Fluid Structure Interaction

BOOK OF ABSTRACTS



9 – 11 July 2025

Vienna, Austria

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Euromech Colloquium 654 –Program

Wednesday July 9, 2025

8:00-9:00	Registration
8:50-9:00	Welcome and opening
	Session #1 – *Chair*: Chandan Bose
9:00-9:25	B. Thiria. “Subtle frequency matching reveals resonant phenomenon in the flight of Odonata”
9:25-9:50	C. García-Baena et al. “Three-dimensional deformation and aerodynamic performance in insect-inspired flapping wings”
9:50-10:15	T. Engels. “Break a wing: numerical aerodynamics of flying insects with damaged wings”
10:15-10:40	S. Saha et al. ”Wing kinematics and drift compensation by *Pantala flavescens* in tailwind and crosswind.”
10:40-11:15	**Coffee Break**
	Session #2 – *Chair*: Karen Mulleners
11:15-11:40	A. Nitti et al. “On the shape-Reynolds number correlation in jellyfish locomotion”
11:40-12:05	A. Hoover & J. Mills “Emergent flow asymmetries from the metachronal motion of the soft flexible paddles of the gossamer worm”
12:05-12:30	T. Steinmann et al. “A morphological innovation enables a several-fold expansion of the ecological niche”
12:30-12:55	Y. Fu & S. Jung “Undulation dynamics inspired by snail and giant larvacean kinematics”
13:00-14:00	**Lunch Break**
	Session #3 – *Chair*: Oscar Flores
14:00-14:25	*Discussion 1*
14:25-14:50	G. Li et al. “An integrated fluid–structure–motion numerical framework for evaluating magnetically actuated soft robot swimming”
14:50-15:15	D. Choi et al. “Design optimization of soft nozzle for rotary propulsors”
15:15-15:40	D. Kolomenskiy et al. “Oscillator conditions in microinsect flight apparatus”
15:40-16:05	A. Khan et al. “Hydrodynamics of insect-like water surface locomotion”
16:05-16:40	**Coffee Break**
	Session #4 – *Chair*: Anne Cros
16:40-17:05	K. Dhileep et al. “Effect of flexion ratio on the performance of propulsive fins”
17:05-17:30	S. Tiomkin & J. W. Jaworski “Unsteady aerodynamic functions for membrane airfoils”
17:30-17:55	N. Sarkar et al. “A GPU-accelerated loosely coupled fluid structure interaction scheme for simulation of flow over mechanical heart valves”

Thursday July 10, 2025

	Session #5 – *Chair*: Ramiro Godoy-Diana
9:00-9:25	N. Widdup et al. “Bio-inspired flight for Martian exploration”
9:25-9:50	M. Iima “Phase-based control mechanisms for flight and swimming under vortex-dominated flows”
9:50-10:15	S. Otomo et al. “Unsteady force evaluation by vortex force map method at Reynolds numbers of 10 – 100”
10:15-10:40	J. Li & C. Bose “Unsteady vortex force analysis of flexible foils subjected to accelerated pitching”
10:40-11:15	**Coffee Break**
	Session #6 – *Chair*: Christiana Mavroyiakoumou
11:15-11:40	G. Raynaud et al. “Shaping up to explore and exploit fluid-structure interactions of leaf-inspired shapes”
11:40-12:05	F. Huera-Huarte “Energy harvesting from VIV using a pendulum with and without wake interference”
12:05-12:30	R. Godoy-Diana et al. “Water-wave interactions with a horizontal submerged elastic plate”
12:30-12:55	K. Ahmed et al. “Fully coupled FSI simulation of a hydroelastic energy harvester with active and passive foil motion”
13:00-14:00	**Lunch Break**
	Session #7 – *Chair*: Marco de Tullio
14:00-14:25	*Discussion 2*
14:25-14:50	M. Khan et al. “Oscillatory foil propulsion in turbulence: Force and velocity fluctuations over a pitching foil”
14:50-15:15	S. Olivieri et al. “Bio-inspired flapping flight in a turbulent free stream”
15:15-15:40	A. Gayout & D. Lentink “Turbulence enhances bird tail aerodynamics”
15:40-16:15	**Coffee Break**
	Session #8 – *Chair*: Melike Kurt
16:15-16:40	H. Liu & D. Y. Wang “An active wall-turbulence drag reduction mechanism using dolphin-inspired skin microvibrations”
16:40-17:05	L.-U. Schrader & D. Das “Bio-inspired compliant coating for low-drag underwater drone”
17:05-17:30	C. Mavroyiakoumou et al. “Modeling flying formations as flow-mediated matter”
17:30-17:55	L. Chao & L. Li “Embodied hydrodynamic interactions in engineered and biological systems”
19:30	**Conference dinner**

Friday July 11, 2025

	Session #9 – *Chair*: Manuel Garcia-Villalba
9:00-9:25	A. Goza et al. “A compliant flapping flat plate with heterogeneous, aerodynamically optimal flexibility properties”
9:25-9:50	H. Saddal & C. Bose “Fluid-structure interaction of bio-inspired flexible flaps and morphing foils”
9:50-10:15	C. L. Jawetz et al. “Efficient undulatory swimming through engineered stiffness gradients”
10:15-10:40	F. Bouard et al. “Examination of bending rules in nature”
10:40-11:15	**Coffee Break**
	Session #10 – *Chair*: Swathi Krishna
11:15-11:40	J. G. Rivas-Iñiguez et al. “Oscillating reconfiguration of two side-by-side flexible plates”
11:40-12:05	N. Silin et al. “Flexible foil dynamics under shear flow: stabilization through spanwise modulation”
12:05-12:30	J. M. Camacho-Sánchez et al. “The effect of degrees-of-freedom on self-adaptive flaps for 3D blunt body drag reduction”
12:30-12:55	A. B. Menon et al. “Thrust enhancement due to reorientation of pressure field by deforming flexible surface attached to a flapping foil”
13:00-14:00	**Lunch Break**
14:00-14:15	Closing remarks
14:30-15:30	**Visit to Secession Museum**

Subtle frequency matching reveals resonant phenomenon in the flight of Odonata

B. Thiria

In this work, we investigate the connection between the flight flapping frequency and the intrinsic wing properties in Odonata (dragonflies and damselflies). For such large flying insect species, it has been noted that the wingbeat frequency is significantly lower than the structural resonance of the wing itself. However, the structural resonance mechanism is often evoked in the literature for flying and swimming animals as a means to increase locomotion performance. Here, we show that the flight of Odonata is based on a nonlinear mechanism that strongly depends on the wingbeat amplitude. For large flapping amplitudes (as observed in natural flight), the resonant frequency of the wings decreases with respect to its value at low amplitudes to eventually match the wingbeat frequency used in flight. By means of this nonlinear resonance, Odonata keep a strong wing stiffness while benefiting from a passive energy-saving mechanism based on the dynamic softening of the wing.

Three-dimensional deformation and aerodynamic performance in insect-inspired flapping wings

C. García-Baena[1,2,3], F. J. Parras-Martos[2], R. Antier[3], C. Gutiérrez-Montes[2], J.I. Jiménez-González[2], B. Thiria[3] and R. Godoy-Diana[3]
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[2] Universidad de Jaén, Spain
[3] ESPCI Paris Université PSL, France

We study the link between wing deformation and aerodynamic force production of an insect-inspired two-vein flexible flapping wing model. The 3D deformation of the wings is monitored experimentally while, simultaneously, the instantaneous aerodynamic forces are recorded with a force balance. We show that the optimal wing stiffness distribution, controlled by the angle β between the leading edge and radial veins, results from a subtle passive control of the phase lag between the leading and trailing edges of the wing. Furthermore, the wing behavior is coupled with its stiffness, being the wing deformation linked to the proximity of the beating frequency to its natural mode of vibration (Ramananarivo et al. (2011)), through a modal analysis of the wing structure we have observed that the first mode of natural vibration makes almost no difference between veins angles, but it is in the second one where some deviations are found. Finally, to complement the experimental results and understand the flow along the flapping cycle, a numerical simulation with moving mesh, extracted from the captured experimental 3D points, has been developed.

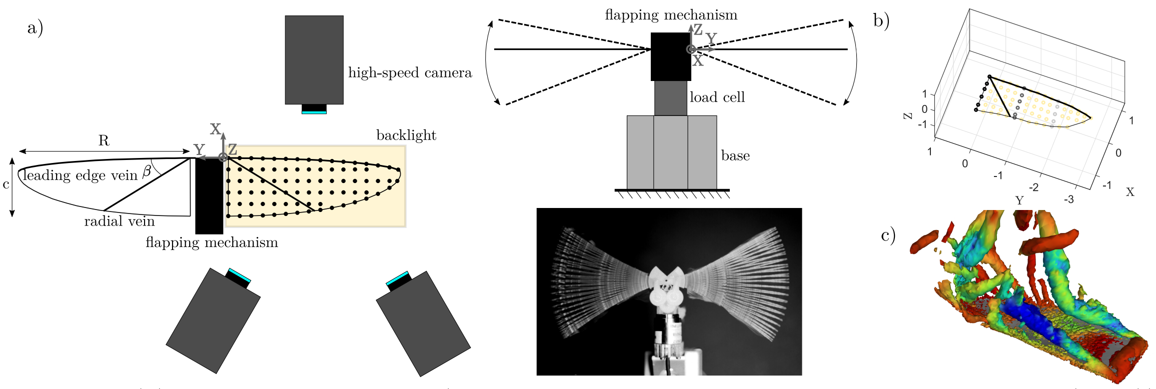

Figure 1: (a) Experimental setup (reproduced with permission from Antier et al. (2024)), (b) three-dimensional reconstruction of the wing and (c) Q-criterion iso-surface obtained numerically colored by the static pressure.

References

S. Ramananarivo, R. Godoy-Diana, B. Thiria PNAS of the USA, 108(15), 2011

Antier, R. and Thiria, B. and Godoy-Diana, R. Journal of Fluids and Structures, 124, 104043, 2024.

Break a wing: numerical aerodynamics of flying insects with damaged wings

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[1] CNRS & Aix-Marseille Université,
UMR 7287, Institut des Sciences du Mouvement Etienne-Jules Marey

Flying insects, spectacular little flapping machines with enormous evolutionary success, are an invaluable source of inspiration for a large, interdisciplinary community of scientists. In this talk I will show our latest results on the aerodynamics of houseflies (*M. domestica*) and dragonflies (*P. flavescens*) flight with broken wings, with a focus on the numerical aspects of this work. We combine wing wear experiments, in which we study how wing damage progresses over time, with state of the art numerical simulations of the aerodynamics of animals with broken wings. The numerical simulations are done with our in-house open-source solver `WABBIT`, which combines wavelet-based adaptivity with an efficient parallelization to exploit massively parallel supercomputers. It will be presented in some detail in this talk. From those high-fidelity data, we obtain a data-driven quasi-steady aerodynamic model, which, combined with the full-scale simulations, allows us to explain the energetic cost of flying with broken wings. This insight allows us to draw conclusions on the reserve animals are built with, which a potentially important guideline for the design of aerial robots, as well as an important factor for biological fitness.

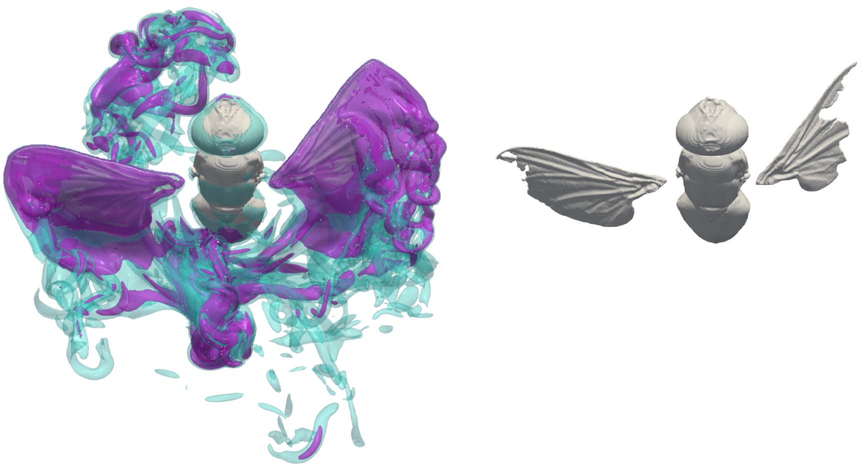

Figure 1: A housefly with severely damaged wings in climbing flight. Shown is the vorticity generated by the wings, using the predicted kinematics adjustments required to compensate for the damage.

References

[Engels2021] T. Engels, K. Schneider, J. Reiss and M. Farge, A wavelet-adaptive method for multiscale simulation of turbulent flows in flying insects, Commun. Comput. Phys., 30, 1118-1149.

Wing kinematics and drift compensation by *Pantala flavescens* in tailwind and crosswind

Sandeep Saha[1], Kumar S. Ranjan[1], Amit A. Pawar[1] and Arnab. Roy[1]
[1] Department of Aerospace Engineering, Indian Institute of Technology Kharagpur, West Bengal, India. Pin - 721302.

Pantala flavescens performs a multi-generational transoceanic migration between India and Africa (see Figure 1a), where wind drift compensation is crucial.[1] We conducted tethered flight experiments (Figure 1b: top and middle) in a wind tunnel at a wind speed of 2.7 m/s on specimens of *P. flavescens*. Specifically, we evaluated the tethered flight in the tailwind and headwind for different crosswind orientations (Figure 1b: bottom) by comparing the distribution of mean values of thrust, side force, and lift between the headwind and the tailwind (Figure 1c). Further, we conducted high-speed Schlieren flow visualization to visualize two distinct flight modes and the associated vortical flow structures (Figure 1 d).

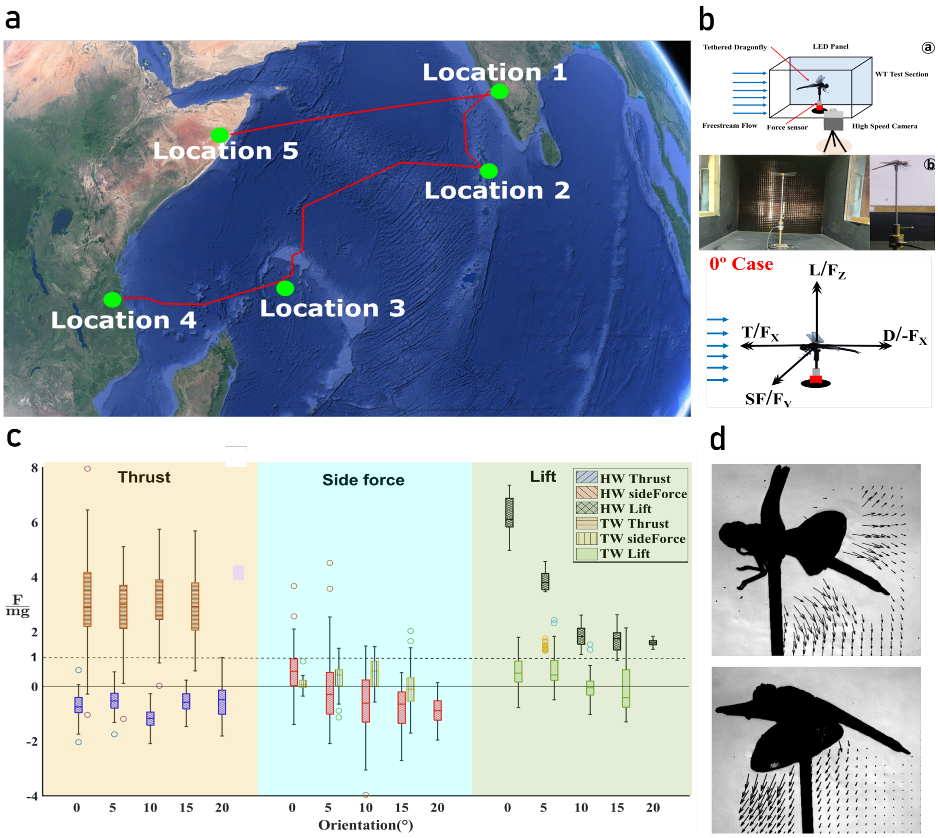

Figure 1: (a) Migration route of *P. flavescens*; (b) Force measurement setup (top: schematic, middle: photograph, and bottom: orientation and force components); (c) Comparison of forces for headwind and tailwind; (d) Flow field for different flight modes (top: normal flight mode, bottom: escape flight mode)

[1]Kumar Sanat Ranjan et al. "Transoceanic migration network of dragonfly Pantala flavescens: origin, dispersal and timing". In: *Frontiers in Ecology and Evolution* 11 (2023), p. 1152384.

On the shape-Reynolds number correlation in jellyfish locomotion

A. Nitti[1], D. De Marinis[1] and M.D. de Tullio[1]
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The first known metazoans to achieve muscle-powered locomotion are jellyfish. Despite their relatively simple biological architecture, they implement efficient locomotion mechanisms, such as jet propulsion or rowing propulsion. The correlation between locomotion and morphology has not been fully understood yet.

Jellyfish motion occurs by converting the volume reduction of the subumbrellar volume into forward thrust. The bell geometry, swimming kinematics, stroke frequency, and vortex dynamics are some of the variables that affect the conversion ratio and propulsion performance. As a result, jet propulsion and rowing propulsion can be achieved either. Jet propulsion is recognized for achieving high peak velocities, while rowing propulsion is associated with lower transportation costs. Despite extensive numerical and experimental investigations into these propulsion methods, there is a notable absence of quantitative assessments regarding the relationship between locomotion performance and bell shape across various scales. This study utilizes a partitioned fluid-structure interaction solver (see Figure 1) to establish these correlations. The excitation-contraction dynamics of the jellyfish body is solved via a NURBS-based Isogeometric analysis, whereas the flow field is advanced by a second-order accurate finite-difference method.

All samples examined are subjected to the same active muscular strain, ensuring kinematic consistency among samples. The resulting fluid-structure interaction mechanism is quantitatively assessed using a Force-Partitioning approach.

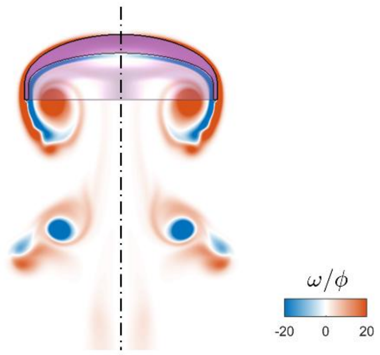

Figure 1: Out-of-plane vorticity generated by a rowing jellyfish; from Nitti et al. (2023).

References

Nitti, A., Torre, M., Reali, A., Kiendl, J., & de Tullio, M. D. (2023). A multiphysics model for fluid-structure-electrophysiology interaction in rowing propulsion. Applied Mathematical Modelling, 124, 414-444.

Emergent flow asymmetries from the metachronal motion of the soft flexible paddles of the gossamer worm

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Metachronal waves are ubiquitous in propulsive and fluid transport systems across many different scales and morphologies in the biological world. Gossamer worms, or tomopterids, are a soft-bodied, holopelagic worm that use metachrony with their flexible, gelatinous parapodia to deftly navigate the midwater ocean column that they inhabit [1]. In the following study, we develop a three-dimensional, fluid-structure interaction model of a tomopterid parapodium to explore the emergent metachronal waves formed from the interplay of passive body elasticity, active muscular tension, and hydrodynamic forces [2]. After introducing our model, we examine the effects that varying material properties have on the stroke of an individual parapodium as well as the resulting fluid dynamics. We then explore the temporal dynamics when multiple parapodia are placed sequentially and how differences in the phase can alter the collective kinematics and resulting flow field.

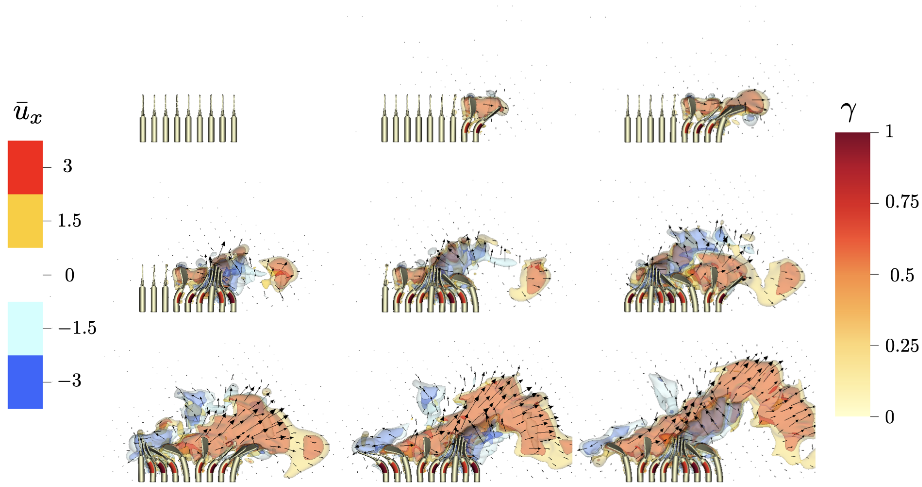

Figure 1: Snapshots of velocity vectors and isocontours of u_x as a wave of tension passes over an array of nine parapodia, with tension magnitude plotted on each parapodia. Strong flow structures are generated during the power stroke (left to right).

References

[2] Daniels J., Aoki N., Havassy J., Katija K., and Osborn K. J. "Metachronal swimming with flexible legs: a kinematics analysis of the midwater polychaete Tomopteris." Integrative and Comparative Biology 61.5 (2021): 1658-1673.

[2] Hoover, A. P. "Emergent metachronal waves using tension-driven, fluid-structure interaction models of tomopterid parapodia" Integrative and Comparative Biology 61.5 (2021): 1594-1607.

A morphological innovation enables a several-fold expansion of the ecological niche

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Maneuvering on fast running waters is an energy demanding task, making this niche hard to access. The propelling fan of the waterstrider *Rhagovelia* is an evolutionary innovation that enhances the maneuverability in these environments. This structure consisting of 20 lamellate branches, each with thinner secondary branches, offers a unique model to understand the tenuous link between morphological innovations and adaptation to new ecological environments. However, the principles of enhanced thrust, i.e. the magnitude of the forces transfer between the fan and the fluid, is not understood. We characterized the kinematics of fan and body of *Rhagovelia* during the propulsion phase. A simplified mechanical model that replicates the movement of the fan is used in both experiments and fluid dynamic computations. Using Particle Image Velocimetry, we measured the flow velocity field around it and determined the magnitude of forces using a load cell. Finally, we used computational fluid dynamics to resolve the flow around a numerical fan replicate of similar morphology. The computations, once validated by their comparison with experimental results using similitude principles, allowed us to determine the nature of the forces acting on the fan. A large part of the fan's resistive force is due to viscous shear stress. The 75 % porosity lamellate fan functions as a leaky paddle, while producing 80 % of the hydrodynamic drag force of an equivalent membrane oar. The thrust enables the strider to colonize most streams, expanding its niche by a factor of four to five.

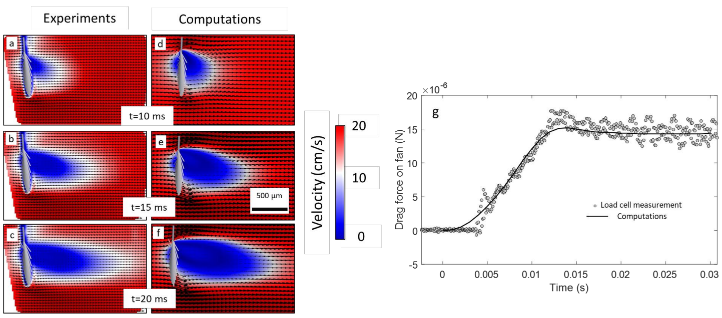

FIGURE 1 – Flow velocity amplitudes obtained with PIV in oil and by computations. (a, b, c) Velocity amplitude and velocity field in horizontal cross sectionnal wakes of the fan as measured by PIV technique. (d, e , f) Velocity amplitude and velocity field in horizontal cross sectionnal wakes of the fan as determined by computational fluid dynamics. (g) Comparison of the total forces acting on the fan measured with the load sensor in oil and obtained by computations.

Undulation Dynamics Inspired by Snail and Giant Larvacean Kinematics

Y. Fu[1] and S. Jung[1]
[1] Cornell University, USA

Microplastic pollution presents a growing crisis in aquatic environments, where current remediation methods such as tow nets and propeller-based suction suffer from limited maneuverability and ecological disruption. Inspired by the efficient fluid/particle transport mechanisms of snails Pandey et al. (2023) and Giant Larvaceans, we present a modular, bioinspired robotic system capable of dual-mode fluid pumping and propulsion.

The system comprises a flexible sheet with spatially varying rigidity, actively undulated at the anterior while allowing passive flapping along the posterior. Parametric experiments varying actuation frequency (0.5-9 Hz), flexural rigidity, and trailing edge attachment reveal nonlinear trends in both pumping flow rate (Q) and thrust (T). Three distinct regimes of Q emerge, with a resonance-linked plateau and two linear ranges. In contrast, T increases continuously across frequencies with regime-dependent slopes. Flow visualization through phase-averaged vorticity and Lagrangian Coherent Structures indicates regime transitions correspond to wake vortex structure shifts. Theoretical modeling using Euler-Bernoulli beam theory and elongated-body theory provides predictive insight into force generation and pumping effectiveness. The integrated robotic prototype demonstrates promising capabilities for maneuverable and low-intrusion microplastic collection, advancing the design of environmentally responsible aquatic robots.

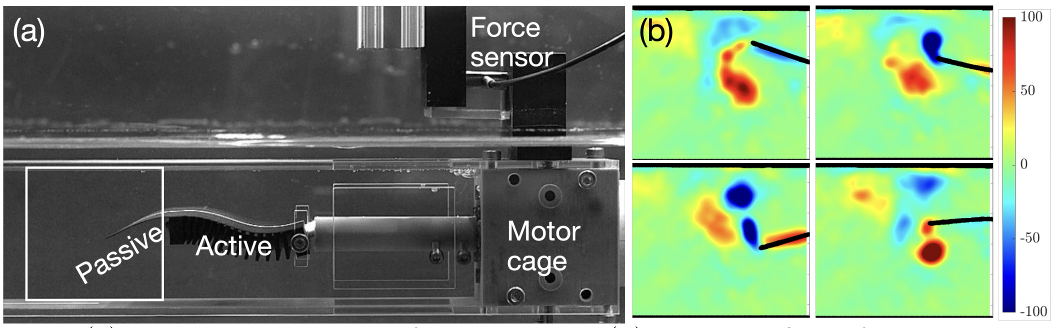

Figure 1: (a) Experimental setup of a undulator. (b) Vorticity fields from Particle Image Velocimetry near the tip of the passive sheet.

References

Pandey, Anupam, Zih-Yin Chen, Jisoo Yuk, Yuming Sun, Chris Roh, Daisuke Takagi, Sungyon Lee, and Sunghwan Jung. "Optimal free-surface pumping by an undulating carpet." Nature communications 14 (2023): 7735.

An Integrated Fluid–Structure–Motion Numerical Framework for Evaluating Magnetically Actuated Soft Robot Swimming

G. Li[1], D. Kolomenskiy[2], B. Thiria[3], R. Godoy-Diana[3], T. Engels[4]
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Micro-scale swimming robots show immense potential for operations in confined environments with minimal invasiveness. To address energy supply, propulsion, and control constraints, external magnetic fields are commonly employed for both actuation and guidance. Such magnetically driven soft robots typically comprise a magnetic core that subject to the magnetic forces and elastic body components enabling flapping or undulating motion.

Predicting the motion and kinematics of these robots is challenging, given the interplay between structural deformation and fluid dynamics. To overcome this hurdle, we present an integrated fluid–structure–motion (FSM) numerical framework. The approach combines three coupled modules that respectively resolve fluid flow, elastic deformation of the structure, and free motion of the robot. While the model requires basic swimmer and fluid properties—such as geometry, material characteristics, density, and viscosity—the only additional external input is the prescribed magnetic field.

This FSM framework accurately captures the motion of magnetically driven soft robots, facilitating the virtual assessment of swimming patterns and propulsion performance. Furthermore, it may provide fresh insights into fish-like locomotion and hydrodynamic interactions, illuminating fundamental principles of bio-inspired swimming and potentially guiding future robot design.

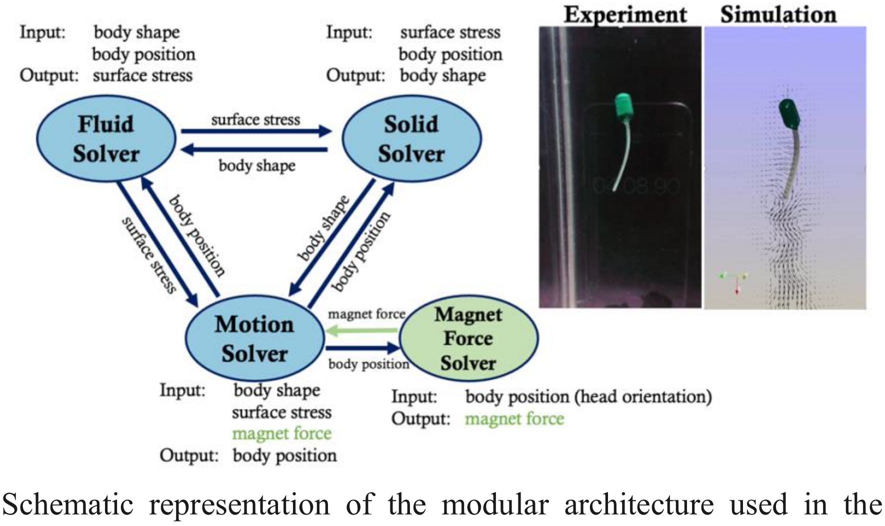

Figure 1: Schematic representation of the modular architecture used in the integrated numerical method, along with both the experimental and simulated images of the magnetically actuated soft robot.

Design optimization of soft nozzle for rotary propulsors

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[2] Stanford University, Pacific Grove, California, United States
[3] The University of Birmingham, Birmingham, United Kingdom

We optimize a soft nozzle, inspired by a squid's funnel, which surpasses the thrust of a rigid nozzle under the same propeller-induced inflow. To leverage the nonlinear deformation governed by wave propagation, we propose a multi-fidelity Bayesian optimization (MFBO) process that significantly reduces experimental costs while maximizing thrust enhancement. To achieve this, we develop efficient experimental frameworks, including thrust measurement setups and soft material 3D printing, along with a CFD solver based on OpenFOAM–preCICE–Calculix (OPC), enabling strong fluid–structure coupling with tunable fidelity for rapid design space exploration. The nozzle geometry is parameterized by nine variables, including height, average radius, spline-based axial profile, and thickness distribution. We tested 20% of the designs experimentally by measuring thrust with a load cell, while 80% of the nozzle designs were evaluated virtually using the OPC solver at multiple fidelity levels. MFBO, employing Gaussian process regression with a radial basis function kernel, guided the selection of promising new designs while dynamically assessing the fidelity of each data point. Through iterative testing and refinement, we achieved a seven percent thrust improvement over the original design. Using 3D Digital Image Correlation (DIC) and 3D Particle Image Velocimetry (PIV), we identified the fluid–structure interaction mechanisms responsible for this thrust amplification. The final optimized nozzle not only exceeds the performance limits of rigid nozzles but also mirrors key features of natural soft nozzles, suggesting evolutionary evidence for how animal nozzles have adapted to similar flow conditions.

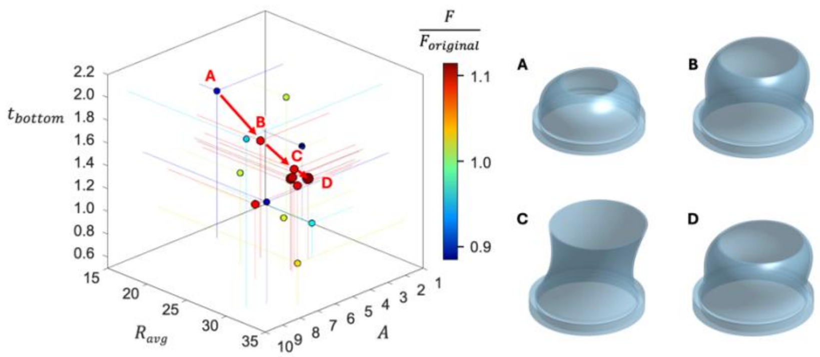

Figure 1: Bayesian optimization process of underwater thrust plotted with the three most influential parameters (R_{avg}, A, t_{bottom}), showing nozzle designs evolving from A to D on the right.

References

Choi, D., & Park, H. (2024). Mechanism of enhanced impulse and entrainment of a pulsed jet through a flexible nozzle. Journal of Fluid Mechanics, 996, A6.

Oscillator conditions in microinsect flight apparatus

D. Kolomenskiy[1], A. Falman[1], V. Dvornikov[1],
S. Farisenkov[2], N. Lapina[2] and A. Polilov[2]
[1] Skolkovo Institute of Science and Technology,
Center for Materials Technologies, Moscow, Russia
[2] Lomonosov Moscow State University, Department of Entomology,
Faculty of Biology, Moscow, Russia

Evidence exists that insects may utilize resonant mechanics during flight to optimize energetic efficiency. However, there is no consensus on whether this effect is general or essential to all insects. Reduced-order oscillator models, representing insect flight motors as one-dimensional viscoelastic systems, emerged over the last years and were used to study moths Gau et al. (2022) and fruit flies Pons (2023). In our work, we extend this kind of modeling approach to analyze resonance properties and energy efficiency of the flight apparatus in microinsects. We acquired physiological data on the volume and sizes of the flight muscles, representative sizes of the thorax and wings, as well as wing kinematic data, to instruct an oscillator model (see Fig. 1). Then we determined its frequency response, and obtained quantitative estimates of the force and power of groups of muscles.

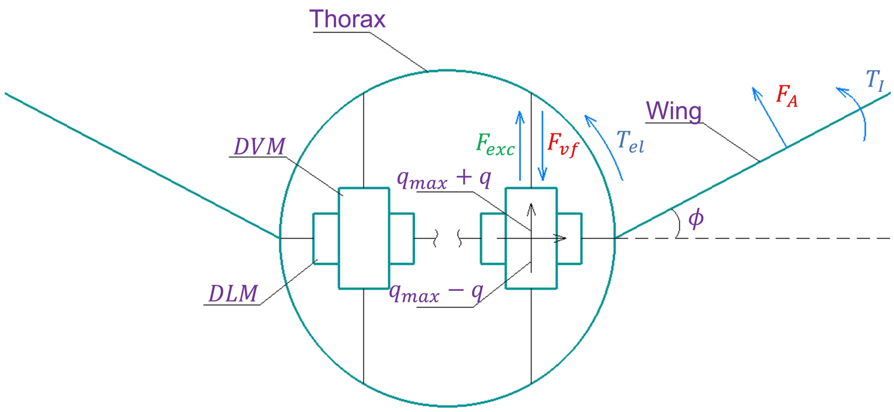

Figure 1: Simplified model of the insect flight apparatus including dorso-ventral (DVM) and dorso-longitudinal (DLM) muscles coupled with the thorax and wings. Forces F and torques T acting on the wing and thorax are shown together with muscle displacement q and wing positional angle ϕ.

This study was supported by the Russian Science Foundation (project no. 22-74-10010).

References

Jeff Gau, Ethan S Wold, James Lynch, Nick Gravish, and Simon Sponberg. The hawkmoth wingbeat is not at resonance. *Biology Letters*, 18(5):20220063, 2022.

Arion Pons. The self-oscillation paradox in the flight motor of *Drosophila melanogaster*. *Journal of The Royal Society Interface*, 20(208):20230421, 2023.

Hydrodynamics Of Insect-like Water Surface Locomotion

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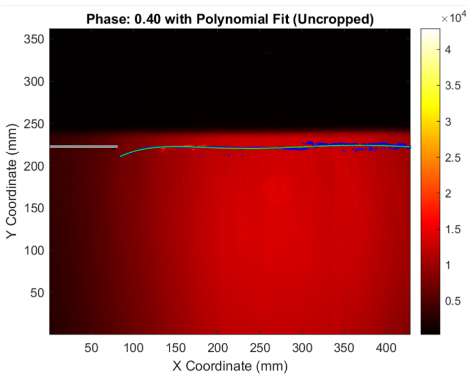
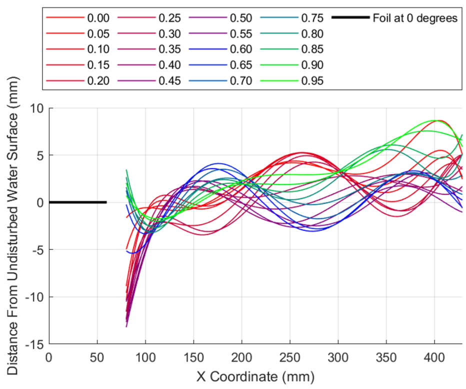
[2] Temasek Laboratories, National University of Singapore, 117411, Singapore
[3]University of Witwatersrand, J1 Jan Smuts Ave, Johannesburg, 2017, South Africa
[4] University of Cape Town, Rondebosch, Cape Town, 7700, South Africa

With the growing use of unmanned aerial vehicles (UAVs), assessing their performance in unexpected scenarios - such as water landings - becomes essential. This project explores flapping propulsion at the air-water interface, inspired by honeybees that adapt their wing movements upon water impact. When stranded on water, honeybees transition from conventional flapping to a hydrofoiling-like motion, generating thrust through surface ripples (Roh and Gharib (2019)). Understanding this mechanism will have significant implications for designing hybrid unmanned systems with lifting surfaces capable of efficient operation in both aerial and aquatic environments.

A combination of experiments and computations are used to systematically explore the connections between the kinematics, flowfields and forces. A custom-built robotic mechanism is used to investigate the effects of a wing pitching on the water surface under quiescent and dynamic flow conditions. Particle Image Velocimetry (PIV) and Planar Laser-Induced Fluorescence (PLIF) provide detailed mapping of flow evolution below and at the free surface respectively. The findings from ongoing experiments will be presented, correlating surface wave patterns (figure 1) with underlying vortex dynamics, turbulence characteristics, and unsteady pitching kinematics.



(a) Example of the surface wave detected based on intensity values. Gray denotes the wing



(b) Phase-averaged wave profiles over a pitching cycle. Colours here indicate the phase

Figure 1: PLIF data capturing the surface waves generated by a pitching wing

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Effect of flexion ratio on the performance of propulsive fins

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Natural swimmers achieve locomotion by producing favourable hydrodynamic conditions through periodic body bending, with passive deformations and active body kinematics contributing to the observed bending patterns. Simplified engineered models that replicate natural swimmers' bending patterns help isolate the effects of flexibility, providing insights into the role of stiffness in animals. Efforts to understand the impact of flexibility on propulsive performance through these models have often yielded contradictory findings. However, most studies have primarily focused on propulsors with uniform flexibility, whereas animals have been reported to have propulsors with non-uniform flexibility (Lucas et al. (2014)). Most studies on propulsor flexibility use restrained setups, like tethered models in quiescent or free stream flow, or models that constrain self-propelled locomotion along the longitudinal axis. In contrast, natural swimmers are unconstrained. Furthermore, in free-swimming cases, efficiency is directly tied to expenditure of stored onboard energy. This study addresses the lack of models exploring non-uniform flexibility in free-swimming propulsors by experimentally investigating propulsive fins with varying flexible regions, characterised by flexion ratio γ, using a free-swimming platform Matsya[2]. Here, a $\gamma = 0$ indicates a fully flexible propulsor (see Fig. 1), while a value closer to $\gamma = 1$ indicates a fully rigid propulsor. The results show that the optimal proportion of rigid and flexible regions in a propulsor depends on swimming requirements: a quarter flexible region ($\gamma = 0.75$) maximizes speed, a quarter rigid region ($\gamma = 0.25$) reduces energetic costs, and an equal proportion of flexible and rigid regions ($\gamma = 0.50$) enhances swimming efficiency. Fully rigid ($\gamma = 1.0$) or largely flexible propulsors ($\gamma = 0.133$) do not provide significant benefits.

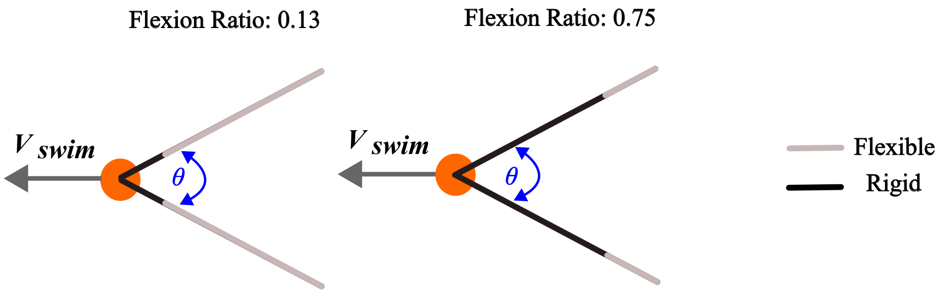

Figure 1: Schematic of a propulsor with a predominantly flexible fin ($\gamma = 0.13$) and a predominantly rigid fin ($\gamma = 0.75$).

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Unsteady aerodynamic functions for membrane airfoils

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A general unsteady aerodynamic theory is developed for one-dimensional, linear extensible membrane airfoils subjected to an unsteady two-dimensional flow. The coupled aeroelastic interactions between the membrane and the surrounding flow are solved exactly in the Laplace domain and are then inverted numerically to determine the unsteady motions of and aerodynamic loads on the deformable membrane. Aeroelastic analogues of the classical unsteady aerodynamic functions associated with Wagner and Küssner for impulsive motions or gust profiles, respectively, and with Theodorsen and Sears for their frequency-domain counterparts are then constructed for membrane airfoils. Structural membrane resonances lead to circular arcs in these frequency-domain functions when viewed in the complex plane, which connect at inflection points associated with the competition for dominance between membrane modes. Results from the predictive model suggest how to passively design or actively adjust the membrane tension to reject unsteady loads at frequencies near resonances.

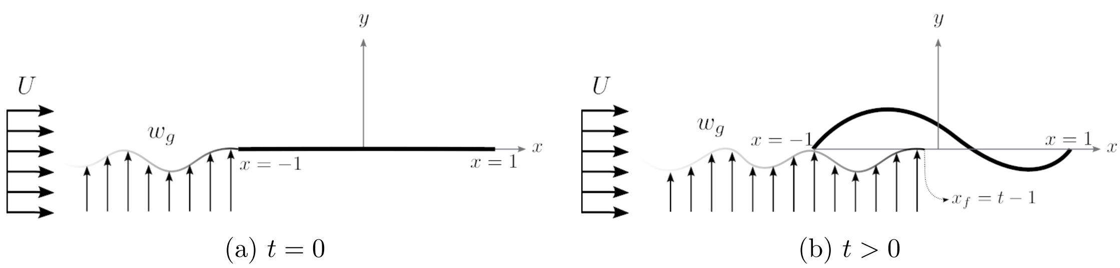

Figure 1: Schematic of the membrane airfoil gust problem: (a) taut and undeformed membrane at initial time $t = 0$; (b) later time $t > 0$; from: Tiomkin & Jaworski (2022).

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A GPU-accelerated loosely coupled fluid structure interaction scheme for simulation of flow over mechanical heart valves

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Mechanical heart valves are reported to induce higher blood damage due to elevated stress levels in the downstream blood flow. Therefore, design improvement for these valves require a detailed understanding of flow features due to the fluid structure interaction of the valve leaflets with pulsatile inflow. A direct numerical simulation (DNS) of flow in mechanical heart valves is computationally expensive and, hence, a graphics processing unit (GPU) optimized immersed boundary solver (Raj et al., 2023) has been used for that. Cartesian mesh blocks with structured diagonal storage for coefficient matrix is deployed to reduce the overall memory requirement. A stable loosely-coupled fluid structure interaction is developed which reduces the computational overheads due to inner iterations. The solver is further optimized for multi-GPU hardware.

A mesh with resolution of the order of Kolmogorov length scale is used for this DNS study. The predicted valve kinematics agrees well with reported literature. The Burger vortex structure as well as fine-scale three-dimensional vortices in the downstream of the valves are captured (Figure-1). The stress levels and resulting blood damage index are predicted. Valve performances at different aortic stenosis levels are also investigated. Further, we have explored different leaflet geometry and proposed a modified leaflet design which alleviates the stress level and results in reduced blood damage index

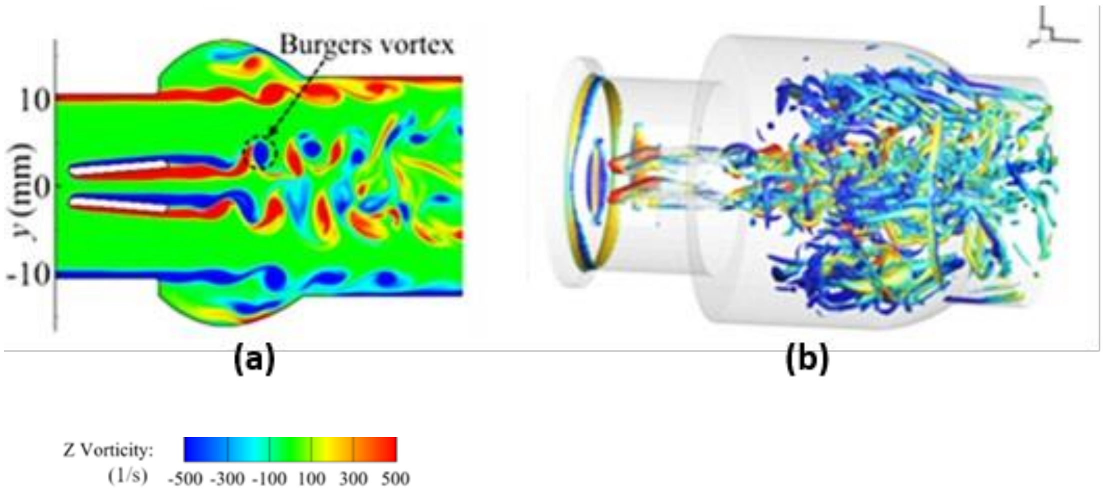

Figure 1: (a) Burgers vortices from the valve leaflests (b) 3D fine-scale vortices as Q=30000

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Bio-Inspired Flight for Martian Exploration

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Recently, bio-inspired flight mechanisms have been identified as a candidate for Martian aircraft design due to their high lift and efficiency in low Reynolds number environments (Pohly et al. (2021)). The low atmospheric density on Mars leads to low Reynolds numbers and moderate-high Mach number (due to the operational speeds required to achieve sufficient lift). While natural flyers fit the low Reynolds number criteria, they also travel at low speeds corresponding to an incompressible flow regime. This research aims to identify the effects of compressibility on aerodynamic force generation of a flexible flapping wing to inform future Martian UAV design. This study is conducted numerically utilising an in-house FSI solver. Details of the solver and validation studies applied to bio-inspired flapping wings and highly compressible flows can be found in our previous works (Wang et al. (2022); Widdup et al. (2025)). This study considers a single, rectangular, flexible, flapping wing in hovering flight. The wing's motion is governed by its rigid leading edge. The stroke angle amplitude is fixed at $A_\phi = 120^o$, while the prescribed angle of attack is varied over the range $\alpha_P = 30^o - 60^o$. Two Reynolds numbers ($Re = 200$ and 2000) are considered in this study and the average leading edge Mach number is incrementally increased over the range $Ma = 0.4 - 1.4$. The wing's flexibility is investigated by considering three frequency ratios ($\omega^* = 0.3, 0.5, 0.7$) which correspond to weakly, moderately and highly flexible wings respectively.

The average lift coefficient was observed to decrease with increasing Mach number, displaying a weakly parabolic (near linear) relationship. This decay is primarily due to the decrease in the lift coefficient peak in the mid-stroke which is attributed to the pressure increase and spanwise flow mitigation of the leading edge vortex induced by shock waves at a sufficiently high Mach numbers. A variation in cyclic lift behaviour and stroke reversal lift peaks was also observed and varied as a function of wing flexibility. This was attributed to the passive deformation and elastic recovery of the wing as well as the relative strength of the vortical structures and the trailing edge–shock interactions. Based on these observations, a compressibility scaling correction factor is proposed to account for lift coefficient degradation due to the weighted effects of pressure, inertial and elastic forces due to wing deformation, wing-shock and wing-vortex interactions.

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Phase-Based Control Mechanisms for Flight and Swimming under Vortex-Dominated Flows

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Understanding fluid-structure interactions in natural flyers and swimmers requires examining vortex dynamics that enable efficient propulsion and manoeuvrability. Prior studies have revealed the significance of vortex interactions in flapping flight and swimming, from symmetry-breaking mechanisms in two-dimensional models (MI & T. Yanagita, 2001) to complex flow-wing interactions in three-dimensional butterfly models (N. Yokoyama et al., 2013) and lift enhancement via interactions between vortices and dragonfly's corrugated wing structures (Y. Fujita & MI, 2023).

Recent advancements have applied the phase reduction theory to these vortex-dominated systems. Phase reduction theory enables the quantification of phase shifts under general external forcing. Our latest study (MI, 2024) developed a phase reduction framework for analysing and optimising lock-in phenomena induced by spatially localised periodic forcing in flow past a flat wing (Fig.1). This approach determines optimal external forces that achieve robust phase-locking with maximal locking range and minimal input energy. In this presentation, we will first outline the fundamental principles of phase reduction theory, and demonstrate how its applications can effectively capture and control essential dynamics in simple fluid-structure interaction problems and bio-inspired flight and swimming.

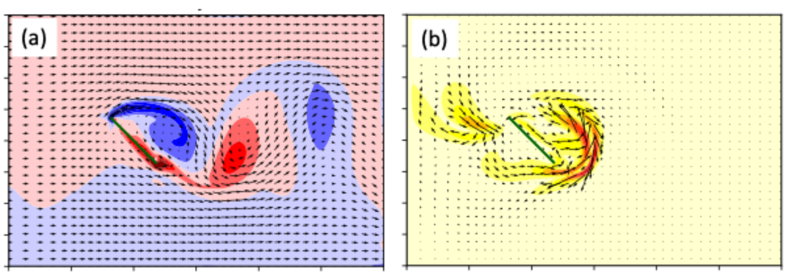

Figure 1: (a) Vorticity field of flow past a flat wing. (b) Phase sensitivity function at the same time of (a); from Iima (2024).

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Unsteady force evaluation by vortex force map method at Reynolds numbers of 10 - 100

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Evaluating unsteady forces at low Reynolds numbers ($Re = \mathcal{O}(10-100)$) is crucial in biological fluid dynamics, in which the direct force measurement is extremely challenging. The vortex force map (VFM) method, developed by Li et al. (2021), is capable of estimating forces from velocity and vorticity fields while also vislualising local contributions of vortex forces. In the VFM method, forces are partitioned into added mass, vortex, viscous pressure, and skin friction forces. Its validity in experimental fluid mechanics was recently confirmed by Otomo et al. (2025). However, the VFM method was only applied to moderately high Reynolds numbers ($Re > 10^3$). This study applies the VFM method to two-dimensional low Reynolds number flows ($Re = \mathcal{O}(10-100)$) where viscous forces come into play. We conduct computational fluid mechanics (CFD) simulations for a cylinder in sinusoidally oscillating freestream. The drag estimated by the VFM method is in reasonable agreement with that obtained by CFD (Fig. 1). The result shows that all four force contributions are important at low Reynolds numbers. The vortex drag visualised in Fig. 1 shows that the separated vortices do not contribute to drag considarably, whereas vorticity surrounding the cylinder surface has a large contribution.

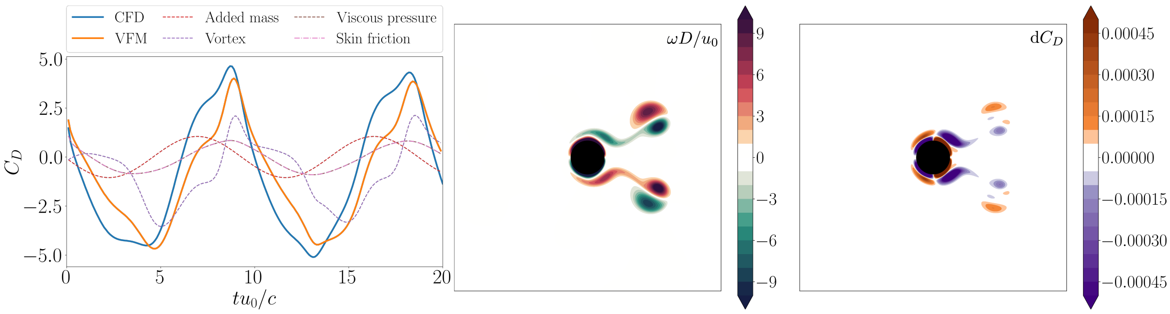

Figure 1: Drag coefficients (left), vorticity (center), and vortex drag contribution (right).

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Unsteady vortex force analysis of flexible foils subjected to accelerated pitching

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Evaluating unsteady forces for reconfigurable bodies is crucial in biological fluid dynamics, in which the direct force measurement is challenging. The vortex force map (VFM) method, developed by Li et al. (2021), is capable of estimating forces from velocity and vorticity fields while also vislualising local contributions of vortex forces. In the VFM method, forces are partitioned into added mass, vortex, viscous pressure, and skin friction forces. However, the VFM method was only developed for single or multiple rigid bodies. This study applies the VFM method to two-dimensional flexible pitching foils in the low Reynolds number regime in the order of 10^3. Shuji et al. (2025) demonstrate its effectiveness in predicting unsteady aerodynamic forces from PIV measurements.

The results obtained from the VFM method are validated against the high-fidelity fluid-structure interaction simulation results. Different bio-inspired airfoils, subjected to an accelerated pitching kinematics, are considered for this study. The incompressible flow-field and the hyperelastic structural responses are obtained through the finite volume method and finite element analysis, respectively. A partitioned strong coupling algorithm is adopted to facilitate the two-way coupling between the flow and structural solvers. The primary objective of this study is to demonstrate the efficacy of the VFM method in estimating the unsteady aerodynamic forces generated by two-way coupled fluid-structure interaction. The finding will provide insights into the role of leading- and trailing-edge flexibility in altering the vortical contributions to generating aerodynamic forces.

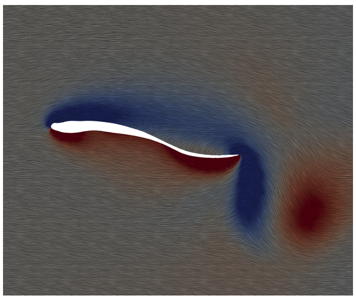

Figure 1: Flow field around a bio-inspired foil undergoing accelerated pitching at $Re = 10^3$.

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Shaping up to explore and exploit fluid-structure interactions of leaf-inspired shapes

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Leaves are examples of flexible structures found in nature that come in a myriad of different shapes and sizes, which might affect the way they interact with the surrounding flow. In this work, we aim to study how the planform shape of leave-inspired flexible sheets or flags affect their flapping dynamics, critical flutter velocity, and the aerodynamic forces they experience. The shape design space of leaves is vast, and only a selected number of shapes could be tested using conventional supervised experiments. To cover and explore a larger portion of the input parameter space, we developed a self-exploring automated experiment using robots that can continuously and in loop fabricate leave-inspired flags with different planform shapes, measure their structural and aerodynamic response, analyse the fluid-structure interactions, and select new flag shapes to test (Figure 1). To optimise and guide the selection of the new flag shapes, we are combining different data-science tools that can help us maximise the information gain with every new experiment and drive exploration to uncover new flapping regimes. The fluid-structure interactions are analysised based on measurement of the force on the flag and of the midline deformations of the flag. The force is obtained using a customised load cell at the root of the flag's pole. The midline deformations of the flag are obtained using an event-based camera (Raynaud and Mulleners , 2025). This self-exploring automated experimental approach will allow us to increase experimental throughput and expedite scientific discovery (Mulleners , 2024).

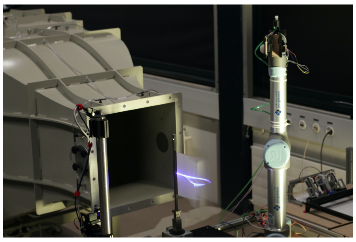

Figure 1: Photograph of the self-exploring automated experimental to study the influence of planform shape on the fluid-structure interaction of leaf-inspired flags.

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Energy harvesting from VIV using a pendulum with and without wake interference

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Although various one-degree-of-freedom configurations have been explored for harvesting energy from vortex-induced vibrations (VIV), the pendulum configuration has not been extensively studied until now. One key advantage of this setup is that all engineering components (generator, transmissions, etc.) can be placed outside the water, with only the cylinder submerged. Additionally, the effects of wake interference on this system remain unexplored.

A series of experiments were conducted in the free-surface water channel at the Laboratory for Fluid-Structure Interaction at Universitat Rovira i Virgili. To minimize the number of tests, experiments focused on reduced velocities near those characteristic of the lock-in response. Without braking torque, the results exhibit the typical one-degree-of-freedom VIV behavior, with dominant frequencies following the shedding frequencies. The loading and response are in-phase at the lowest reduced velocities and out-of-phase otherwise.

When a constant braking torque is applied, the system achieves power coefficients (C_P) between 0.1 and 0.15 within the lock-in region. The highest power coefficients correspond to the largest applied braking levels, where fluid loading is maximized. Figure presents a power coefficient color map derived from over 100 experiments. Additionally, we will analyze wake interference effects by introducing an upstream cylinder to the pendulum system.

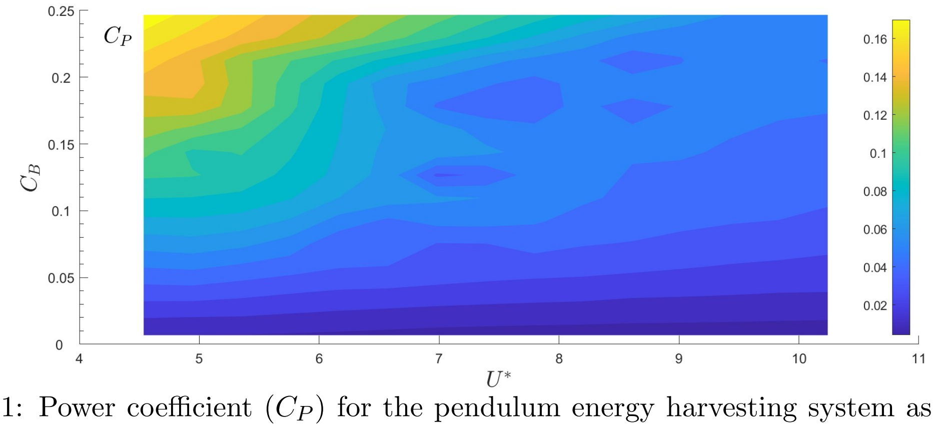

Figure 1: Power coefficient (C_P) for the pendulum energy harvesting system as a function of braking torque (C_B) and reduced velocity (U^*).

Water-wave interactions with a submerged elastic plate

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I will present our work on a submerged elastic plate, clamped at one edge, that interacts with water waves (Polly et al., 2025). Submerged elastic plates have been considered as potentially effective design elements in the development of wave energy harvesters but their behavior in a wave field remains largely unexplored, especially experimentally. Positioned at a fixed depth in a wave tank, the flexible plate demonstrates significant wave reflection capabilities, a characteristic absent in rigid plates of identical dimensions. The experiments thus reveal that plate motion is crucial for wave reflection. Sufficiently steep waves are shown to induce a change in the mean position of the plate, with the trailing edge reaching the free surface in some cases. This configuration change is found to be particularly efficient to break water waves. These findings contribute to understanding the potential of elastic plates for wave energy harvesting and wave attenuation scenarios.

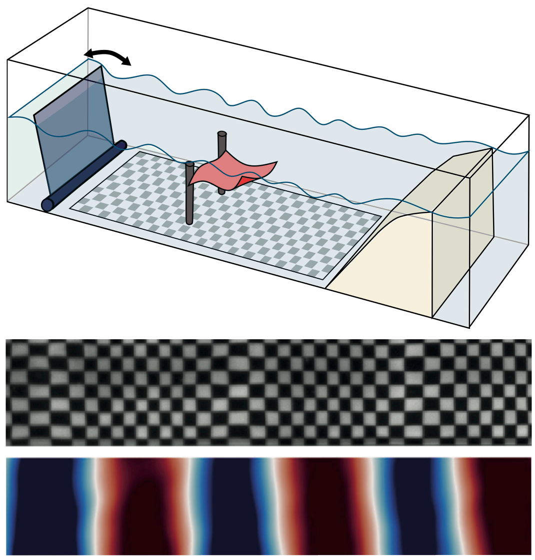

Figure 1: Schematic diagram of an elastic plate in the water-wave flume at PMMH (top), together with a top view visualisation of the checkerboard patter used for Schlieren imaging (middle) and the corresponding surface height measurement (bottom). Red and blue in the colormap represent, respectively, positive and negative deviations of the water surface with respect to the undisturbed surface with no waves.) from: Polly et al. (2025).

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Fully Coupled FSI Simulation of a Hydroelastic Energy Harvester with Active and Passive Foil Motion

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The role of wing deformation in animal propulsion has inspired extensive research in biomimetics, particularly for energy harvesting applications. This study develops a numerical framework to analyze flexible hydrofoils for hydroelastic energy harvesting, where understanding the interplay between fluid dynamics and structural deformation is crucial for optimizing energy extraction through active or passive mechanisms. A fully coupled fluid-structure interaction (FSI) solver (1) was implemented, integrating OpenFOAM for fluid dynamics and CalculiX for structural analysis via preCICE, with a modified overset mesh motion technique ensuring computational efficiency in handling large deformations. Validated against benchmark cases, including rigid heaving foils, the Turek-Hron FSI benchmark, and passive flapping foils, the solver showed strong agreement with established results. Simulations demonstrated that flexibility enhances energy harvesting efficiency, either through active excitation or passive deformation. As shown in Figure (1), increased flexibility led to greater deformation at both edges, earlier vortex shedding, and stronger adverse pressure gradients, enhancing lift and energy extraction. Experimental trials further validate the model and refine its predictive capabilities.

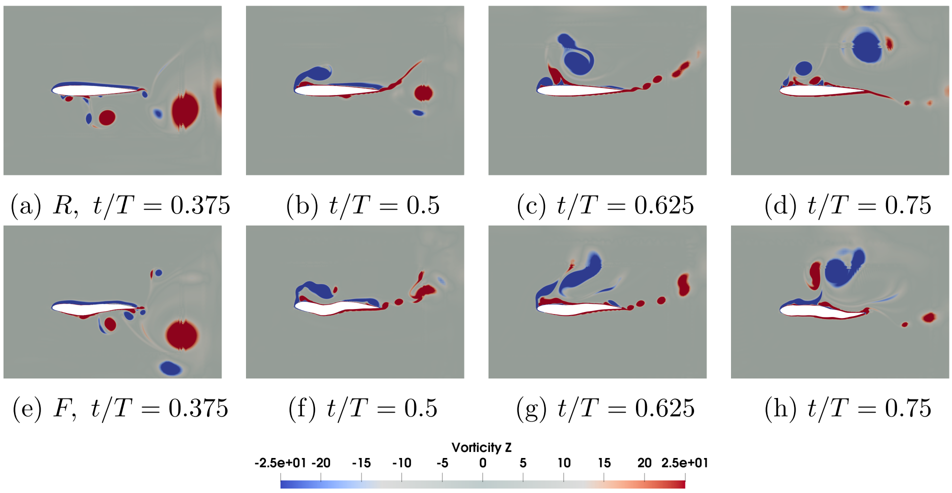

FIGURE 1 – Z-Vorticity Contours for a Rigid (R) and a Flexible Foil (F) (E = 5 MPa) During the Downstroke Phase of a Flapping Cycle

Références

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Oscillatory foil propulsion in turbulence: Force and velocity fluctuations over a pitching foil

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In nature, flyers and swimmers propel themselves through complex flow interactions, navigating free-stream turbulence in the form of currents, waves, gusts, as well as vortex flows generated by nearby individuals. Research has primarily focused on oscillatory foils in laminar flow or periodic vortex-body interactions, where dynamics are governed by control surface length, body speed, and oscillation frequency. However, turbulence's impact on aerodynamic performance remains largely unexplored. With non-linear interactions across multiple scales, free-stream turbulence can introduce perturbations that can either hinder or enhance propulsion and maneuverability, depending on whether interactions are constructive or destructive.

In this work, we experimentally characterized the instantaneous thrust and lift generation of an oscillatory foil in turbulent incoming flow. The experiments were conducted in a water flume, using a hydrofoil prescribed with sinusoidal pitching motions. To generate inflow turbulence, we used an active grid consisting of 7 rotary cylinders with 3d-printed helical strake sleeves, spanning the entire width and depth of the water channel. A parameter survey was conducted for the variation of inflow turbulence intensity from 4 to 8.5% and the chord normalized integral scale from 14 to 25%, as the hydrofoil was pitched with constant motion kinematics at Strouhal number, $St \approx 0/.25$, and chord-based Reynolds number, $Re = 50,000$. Using flow visualization and force measurements, the results from this parameter sweep will be presented in comparison with the forces and flow over the hydrofoil in clean flow.

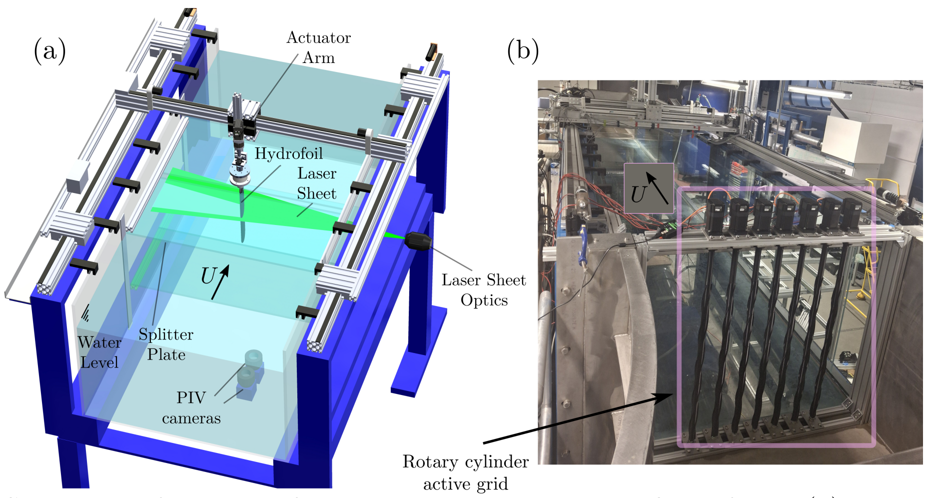

Figure 1: Schematic of the hydrofoil setup indicating the PIV field of view (a), rotary cylinder active grid installation in the water flume(b).

Bio-inspired flapping flight in a turbulent free stream

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Flapping wings are a promising concept for the design of bio-inspired devices, e.g., unmanned micro-aerial vehicles. The latter are typically operating at relatively low flight speeds and altitudes well within the atmospheric boundary layer. In this context, the impact of environmental flow disturbances on the flight performance remains a largely open issue in the development of such aeronautical technology. Here, we investigate how the aerodynamics of a flapping wing with prescribed (heaving and plunging) motion is affected by free-stream turbulence (FST). To this aim, we perform direct numerical simulations using a direct-forcing immersed boundary method for the fluid-solid coupling (fig. 1). The free-stream perturbations are obtained using a synthetic turbulence inflow generator, by means of which we explore the effect of varying two key parameters: (i) the turbulence intensity and (ii) the integral length-scale. A statistical analysis of the results is performed in terms of phase- and spanwise-averaged flow fields as well as thrust, lift and pitching moment aerodynamic coefficients. We show how FST enhances the dissipation of the leading-edge vortices generated by the flapping motion once they are sufficiently downstream, and the consequent modifications in the aerodynamic loads. On one hand, the time-averaged thrust is found to be marginally sensitive to the external disturbances. On the other hand, the characteristic amplitude of the aerodynamic fluctuations is found to scale linearly with the turbulence intensity and sub-linearly with the integral length-scale. A simple mechanism is revealed where FST triggers the leading-edge vortex breakup, which in turns provides the main source of aerodynamic disturbances experienced by the wing. Moreover, we show how the frequency spectra of the aerodynamic fluctuations are governed by the characteristic time-scales involved in the problem. Finally, directions for future work are outlined, focusing on how to devise effective control techniques to mitigate the aerodynamic disturbances induced by FST.

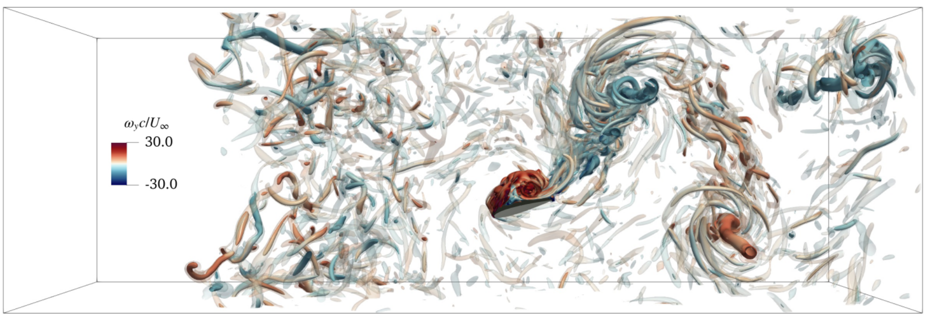

Figure 1: Snapshot from direct numerical simulation of a flapping wing in turbulent free stream (flowing from left to right). The instantaneous vortical structures are detected by means of Q-criterion and coloured with the spanwise vorticity.

Turbulence enhances bird tail aerodynamics

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Turbulence is omnipresent in the environment in which birds fly. In particular, landing mostly happens within the atmospheric boundary layer, often in the direct wake of trees or buildings. This exposes birds to highly turbulent flows whenever they deploy their tails with high angles of attack and various spreads. Maintaining aerodynamic performances in such configuration is especially crucial as flight speed tends to zero. We investigate experimentally the combined effect of spreading and turbulence on a bio-hybrid pigeon tail over its entire range of angles of attack. We present first the effect of spread on the aerodynamic characteristics of the tail, through force measurements and flow visualization. As turbulence is introduced in the upcoming flow, we observe that the spatio-temporal structure of the wake is modified (Figure 1) with an unexpected stabilization, concurring with a remarkable enhancement of the tail aerodynamic efficiency. This beneficial wake-turbulence interaction not only provides insights on bird flight strategies but also bio-inspiration for novel aircraft designs in enhanced turbulence.

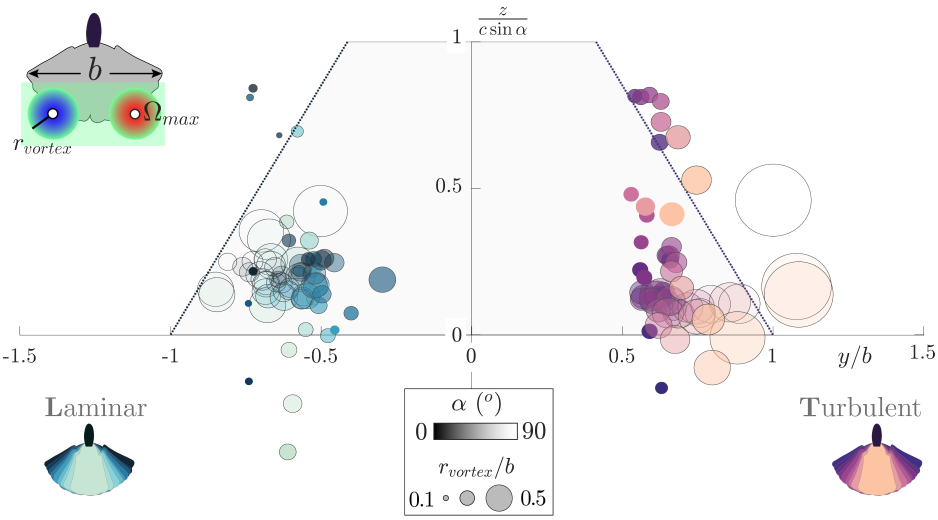

Figure 1: Transverse wake reconfiguration behind the bio-hybrid tail in turbulence for all tested configurations of spread angles (coded in color) and angles of attack (coded in transparency). The core location of the trailing vortices is deviated to the outer trailing edge of the tail and the vortices are wider in turbulent conditions.

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An active wall-turbulence drag reduction mechanism using dolphin-inspired skin microvibrations

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Skin friction drag is a significant source of energy loss and fuel consumption in both animal locomotion and industrial applications, such as manmade vehicles and fuel pipelines. Reducing skin friction drag has been extensively studied through various turbulent flow control strategies. Inspired by the microvibrations observed in dolphin swimming, we recently proposed an active wall-turbulence drag reduction mechanism that uses wall-normal undulating motion actuated by longitudinal micro-ultrasonic waves (LMUWs) with ultrasonic-frequency oscillations and micro-sized amplitudes.

The LES-based results demonstrate that wall-normal turbulent fluctuations are significantly altered within the viscous sublayer of the turbulent boundary layer. This indicates that upstream traveling waves can achieve 100% friction drag reduction, while downstream traveling waves help overcome the tradeoff between friction and pressure drag, resulting in 100% total drag reduction (Wang and Liu, 2024, 2025). Our findings suggest that dynamic skin oscillations create a new dynamic Stokes boundary layer, which has the potential to convert pressure drag into a negative force, thus reducing total drag under the influence of traveling LMUW excitations. This mechanism provides a novel, active, and controllable approach to turbulent drag reduction.

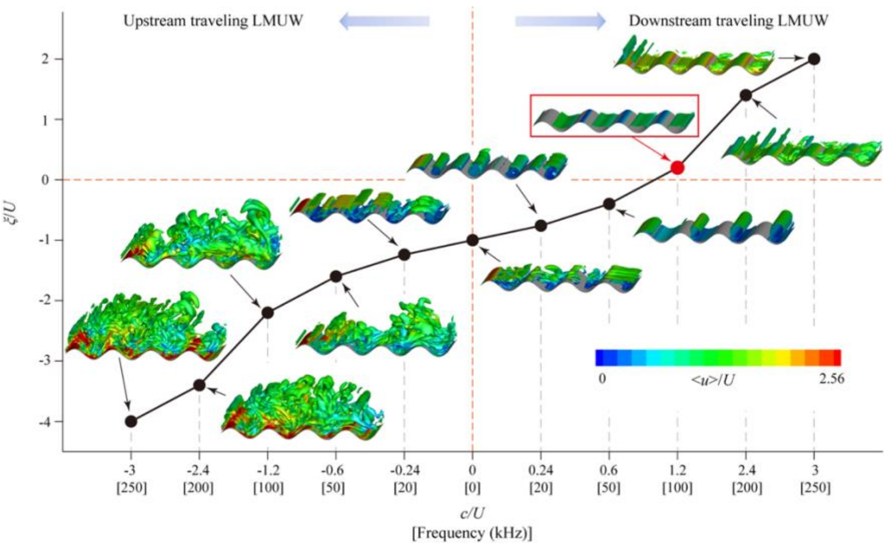

Figure 1: Vortex structures near the oscillating skin surface in terms of ξ/U versus c/U, where ξ, is a relative velocity defined as the difference between the wave speed c and the external flow speed U; from Wang and Liu (2025).

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Bio-inspired compliant coating for low-drag underwater drone

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Autonomous underwater vehicles (AUVs) play a vital role, e.g. in scientific research and the development of infrastructure in the deep sea, relying on low resistance to achieve long operating times on a single battery charge. Here we propose a novel silicone-based compliant coating for AUVs that reduces skin-friction drag. The coating is modelled on the structure of dolphin skin and consists of a thick 'blubber' and a thin 'dermis' (cf. Schrader (2019)). The surface flexibility stabilises the laminar boundary layer along the AUV against Tollmien-Schlichting waves and thus delays natural transition to turbulence. We demonstrate the effectiveness of this coating by numerical simulations of the laminar baseflow profiles (Figure 1b) around the X-35 drone (Figure 1a) using the spectral element code nek5000. Linear stability calculations with an in-house Orr-Sommerfeld solver are performed for these profiles to calculate instability diagrams (Figure 1c): Thanks to the soft coating, the unstable area in the downstream part of the boundary layer (most relevant for the transition) shrinks, while it grows in the upstream part. In the final paper we will present the resulting shift of the transition point and the degree of drag reduction achieved.

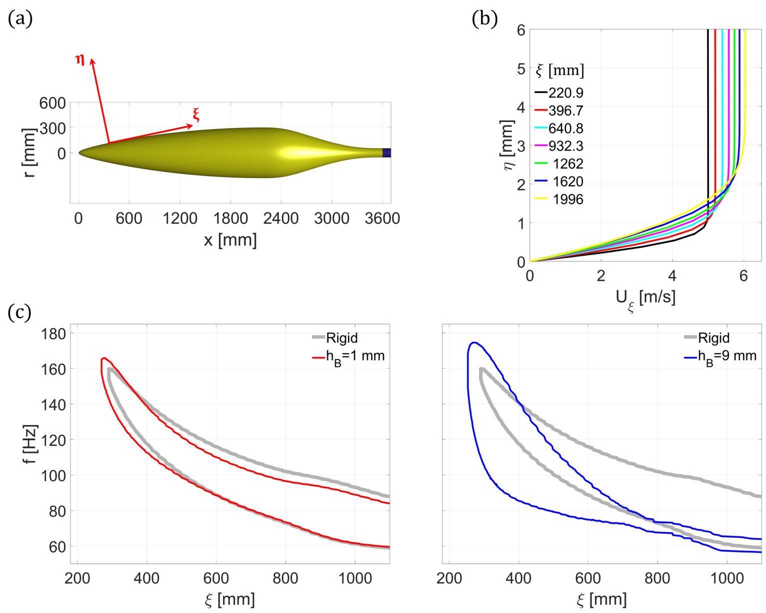

Figure 1: (a) X-35 drone ($L = 3.6$ m, $D_{\max} = 0.6$ m) with body-fitted coordinates ξ and η. (b) Baseflow profiles at various streamwise stations along the body surface. (c) Instability diagrams: Region of unstable waves in the boundary layer over the rigid drone surface as compared with a compliant surface of 1 mm thickness (left) and 9 mm thickness (right).

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Modeling flying formations as flow-mediated matter

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Collective locomotion of flying animals is fascinating in terms of individual-level fluid mechanics and group-level structure and dynamics. In this talk, I will introduce a model of formation flight that views the collective as a material whose properties arise from the flow-mediated interactions among its members. It builds on an aerodynamic model that describes how flapping flyers produce vortex wakes and how they are influenced by the wakes of others. Long in-line arrays show that the group behaves as a soft "crystal" with regularly ordered member "atoms" whose positioning is susceptible to deformations and dynamical instabilities. Perturbing a member produces longitudinal waves that pass down the group while growing in amplitude; with these amplifications even causing collisions. The model explains the aerodynamic origin of the spacing between the flyers, the springiness of the interactions, and the tendency for disturbances to resonantly amplify. Our findings suggest analogies with material systems that could be generally useful in the analysis of animal groups.

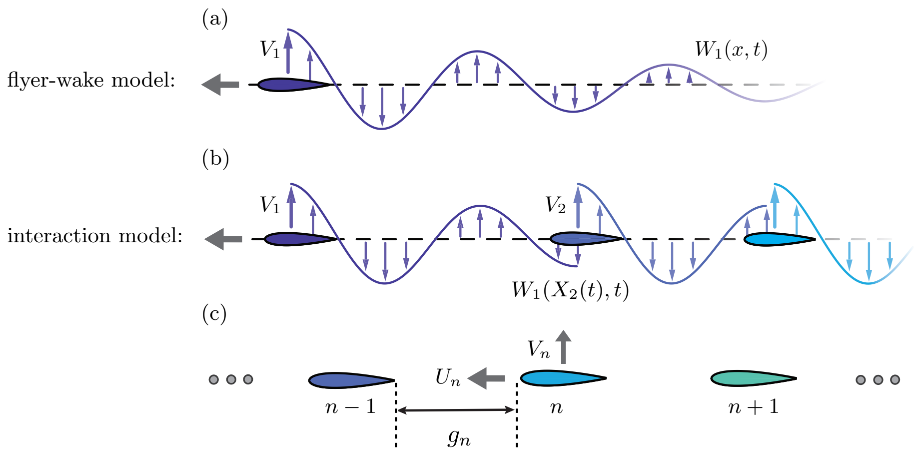

Figure 1: Schematic diagrams of a model of wake generation and interaction. (a) A flyer emits a time-decaying wake whose speed directly reflects its flapping speed V_1. (b) A model to simulate the group dynamics with one-way, nonreciprocal interactions that have memory. (c) Idealized problem of a linear formation of flapping flyers indexed by n, each with prescribed vertical oscillations V_n and free forward flight motions U_n. Here, g_n is the gap distance between flyer n and its upstream neighbor $n-1$.

Embodied hydrodynamic interactions in engineered and biological systems

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Fish swimming in groups provides numerous advantages, including predator avoidance, improved hunting efficiency, and enhanced swimming performance. Traditionally, these collective behaviors have been studied under the assumption of active cognitive control. However, passive embodied hydrodynamic interactions, initially proposed by Lighthill, have also been hypothesized to contribute to stable group formations, though previous studies often relied on simplified one-degree-of-freedom motions and idealized swimming dynamics. In this study, we first introduce a computational model enabling fish to exhibit diverse swimming behaviors with complete two-degree-of-freedom motion. Our results demonstrate that stable formations typical of schooling behavior can emerge purely from embodied hydrodynamic interactions, eliminating the necessity for active cognitive control. We further develop a simplified toy model with minimal input parameters to characterize the resulting embodied schooling behavior. To validate our model, we conducted experiments using robotic and live fish within various laminar flow conditions. Experimental results confirmed that both biological and engineered systems can achieve stable group formations without relying on sensory inputs such as vision or lateral line. Our findings suggest that embodied hydrodynamic interactions play a complementary, secondary role alongside sensory-driven behaviors in collective swimming.

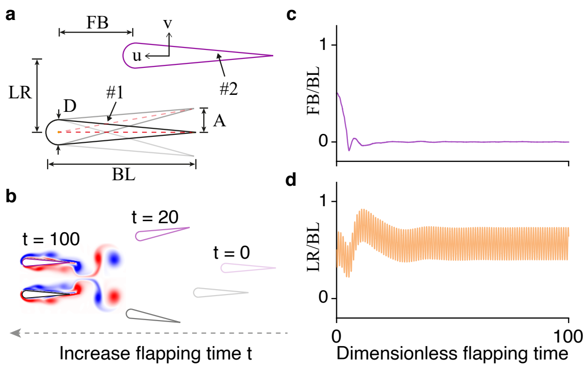

Figure 1: **Preliminary studies on Lighthill's conjecture in 2-DOF motions**. **a** Geometric parameters and configuration of two identical foils (#1 and #2). Each foil has a semicircular leading edge with a diameter (D) and body length (BL), with a ratio of $D/BL = 1/6$. The foils move in both the swimming (u) and lateral (v) directions. The maximal tailbeat amplitude is denoted as A. Parameters FB and LR quantify front-back and left-right separations based on the pitching centers of the foils. **b** Sketch of the generated flow pattern in preliminary studies. **c**, **d** Time-dependent dimensionless front-back and left-right separations between the foils, represented as FB/BL and LR/BL, respectively.

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A compliant flapping flat plate with heterogeneous, aerodynamically optimal flexibility properties

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Insects' flight capabilities have inspired a host of micro-air vehicle designs, many of which have adopted various features of the heterogeneous flexibility of an insect's wing. Despite this prevalence of bio-inspired, heterogeneously flexible engineered wings, there remains an unanswered, tantalizing question: are heterogeneous features of insect wings—even relatively universal ones such as reinforced leading edges and localized stiffness via veins— aerodynamically optimal or even beneficial?

In this talk, we begin to address this question via gradient-based optimization applied to a high-fidelity, fully coupled fluid-structure interaction (FSI) solver. We will focus on two-dimensional (2D) simulations, with the "wing" modeled as a flapping flat plate whose dynamics are governed by a (geometrically nonlinear) Euler Bernoulli beam with variable material properties. Insect-relevant plate kinematics and Reynolds numbers will be prescribed, and the structural properties will be optimized using thrust- and efficiency-based cost functionals. We will compare results from the optimized cases to appropriately chosen uniform property configurations. The results will allow an assessment of how structural heterogeneity can be harnessed to alter key flow structures (such as the leading edge vortex) to benefit flight. We will also draw connections (or lack thereof) between aerodynamically beneficial structural heterogeneity and features of insect wings, as appropriate. This study also serves as a spring board for subsequent 3D studies involving more complex wing shapes, plate properties, structural models, and kinematics.

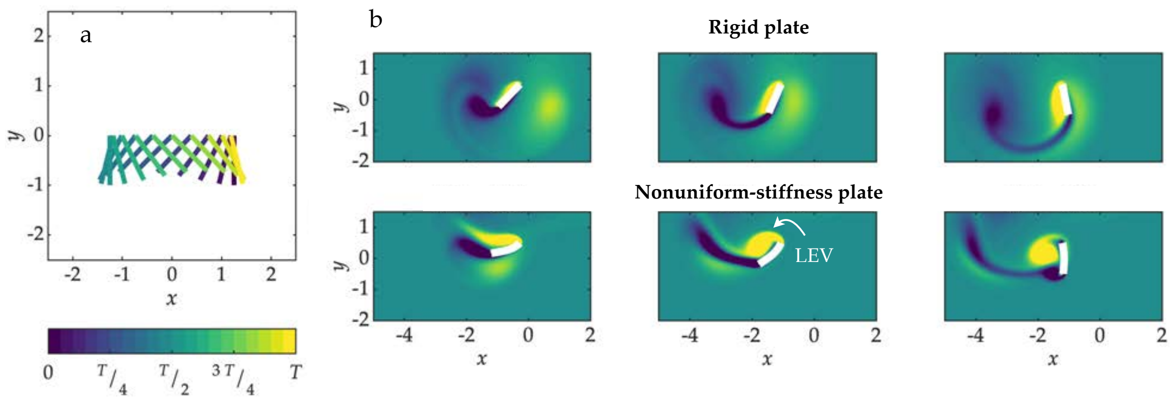

Figure 1: Sample kinematics (a) and high-fidelity simulation results (b) for a flapping flat plate that is rigid (b, top) and compliant with prescribed non-uniform (cubic) stiffness (b, bottom). In the talk, the material distributions will be optimized, and aerodynamically optimal parameters will be connected to the impact on key flow structures such as the leading edge vortex (LEV).

Fluid-Structure Interaction of Bio-Inspired Flexible Flaps and Morphing Foils

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This study investigates the fluid-structure interaction dynamics of bio-inspired flexible flaps and morphing foils [1] in the low Reynolds number regime and the ensuing effect on the overall aerodynamic performance. The primary objective is to understand the influence of governing parameters, including dimensionless bending rigidity ($K_B = \frac{EI}{\rho_f U_\infty^2 L^3}$) and mass ratio ($\mu = \frac{\rho_s h}{\rho_f L}$)/density ratio ($\rho^* = \frac{\rho_s}{\rho_f}$) on the wake dynamics, where EI is the bending rigidity, ρ_f is the fluid density, ρ_s is the solid density, U_∞ is the free-stream velocity, h and L are the thickness and the length of the flap, respectively. The fluid part is governed by the incompressible Navier-Stokes equations and is solved using the finite volume method. A finite element method is employed for the structural simulation. A partitioned strong coupling algorithm, based on the Interface Quasi-Newton Inverse Least Squares (IQN-ILS) acceleration scheme, is adopted to facilitate the coupling between the flow and structural solvers. The data mapping at the fluid-structure interface is manifested through the radial basis function thin plate spline scheme. The present findings show that by tuning the flexibility of the covert-inspired flexible flaps and optimising their locations, the stall can be delayed, resulting in increased lift. On the other hand, we also concluded that passive morphing could be exploited to mitigate the spatial-temporal gust effects, improving aerodynamic efficiency. The underlying vortex-dominated flow physics is investigated in detail. Refer to the representative results for these two cases in Figure 1. By enhancing lift and improving stall control, this research contributes to optimising the flight performance of micro air vehicles or unmanned aerial vehicles in challenging conditions, including gusty winds and complex manoeuvres.

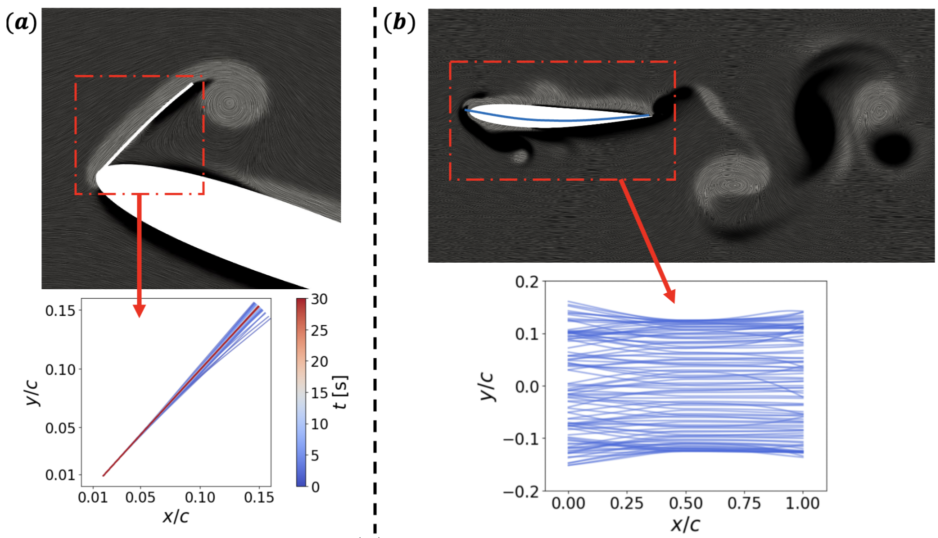

Figure 1: Representative results: (a) leading-edge vortex separation delay through self-excited vibration of flexible flaps; (b) gust mitigation by passive morphing of flapping foils.

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Efficient Undulatory Swimming through Engineered Stiffness Gradients

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Fish achieve remarkable thrust and efficiency in undulatory swimming by leveraging their elastic bodies and fins, a capability we are still unable to replicate when designing underwater drones and energy harvesting devices. Fish swimming performance stems from their ability to actively control their bending patterns by harnessing distributed muscle actuation and body elasticity. It is believed that standing wave oscillations characteristic of thunniform fish locomotion are beneficial for fast swimming, whereas anguilliform swimming with traveling waves yields a more efficient propulsion. Computer simulations and experiments (Demirer et al., 2022; Leroy-Calatayud et al., 2022; Yeh et al., 2017) show that elastic fins with a tapering thickness drastically outperform uniform fins in generated trust and efficiency. Their excellent hydrodynamic performance is associated with their ability to generate traveling waves due to the acoustic black hole effect (Demirer et al., 2022). However, the optimal tapering shape leading to the most efficient locomotion remains unknown.

We use fully-coupled three-dimensional fluid-structure interaction (FSI) simulations to explore the effects of distributed elasticity on undulatory swimming. The high computational cost limits our ability to explore the vast parameter space of this FSI problem. To address this challenge, we deploy a two-stage machine learning (ML) approach based the Fourier neural operator (FNO) (Li et al., 2020) where the kinematics is first learned from the fin thickness distribution, and then the hydrodynamic forces are learned from the fin kinematics. Trained using full-scale FSI simulations, our surrogate ML model demonstrates consistent accuracy across a wide range of fin parameters while dramatically reducing computational cost. We integrate the surrogate model into an evolutionary genetic algorithm (EGA), enabling efficient multi-parameter optimization of fin hydrodynamic performance across thousands of generations in the design space. This approach allows us to identify the best performing designs of tapered fins with superior hydrodynamic thrust and efficiency.

Support from the National Science Foundation (CBET 2217647) is gratefully acknowledged.

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Examination of bending rules in nature

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Recent observations on a large number of flying/swimming animals (Lucas et al. , 2014) have revealed common bending patterns in the animal propulsor deformation during flapping flight/swim. In particular, it has been observed that flexion location and angle typically cluster around $0.65R$ (R is the radius of the wing) and $\theta_0 \approx 25°$ (Figure 2). However, it remains unclear whether natural species have converged towards these flexion location and angle for propulsive efficiency purposes or not. The present study focuses on the role of those parameters on aerodynamic performance of a flapping wing under hovering flight conditions.

The wing undergoes a flapping kinematic consisting in sinusoidal revolving ($\dot{\phi}$) and pitching ($\dot{\alpha}$) motions as shown on Figure 1. The wing flaps over $\phi_0 = 120°$ and reaches $\alpha_0 = 45°$ at mid-stroke. StarCCM+ flow solver is used to directly solve the Navier-Stokes equations using a cell-centered finite volume method around rigid and actively bending wings. Bending is here in phase with the flapping motion. Flexion location r/R and angle θ_0 are systematically varied along from 0 to 1 and 0° to 45°, respectively. Figure 2 shows the efficiency $\left(\overline{C}_L/\overline{C}_P\right)$ contours of the different parameter combination.

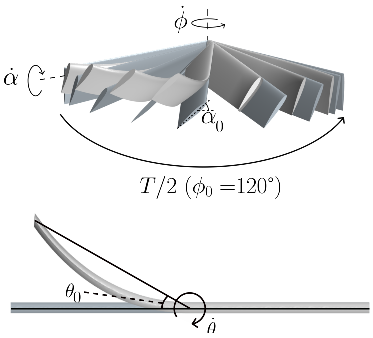

Figure 1: **Illustration of a flapping kinematic.**

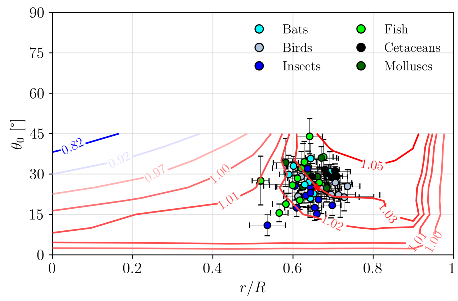

Figure 2: **Bending rules parameters and efficiency contours.**

Efficiency can be improved by 4.8% for animal flexion location and angle with respect to a rigid wing (Figure 2). At the wingtip and for a relatively high θ_0, the efficiency can be further increased up to a difference of 8.7% compared to a rigid wing. This study also highlighted a maximum lift production, increased by 11.2% compared to a rigid wing, (not shown here) with flexion location and angle $r/R = 0$ and $\theta_0 = 25°$, respectively. The final presentation will discuss on the physics underlying these observations

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Oscillating reconfiguration of two side-by-side flexible plates

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A flexible plate submitted to a transversal airflow is statically deflected. Its profile is estimated from the equilibrium between the drag force and the plate's elastic flector moment ; the corresponding phenomenon is called "reconfiguration" (Gosselin et al. , 2010; Alben et al. , 2004). In this experimental work, a second, identical plate is placed by its side and we observed spontaneous out-of-phase oscillations from a critical air velocity. The out-of-phase oscillations allow indeed to increase the free space between the plates so that the airflow is less blocked. Experimental measurements of the amplitude and oscillation frequency are reported and a first model is proposed to explain our experimental results.

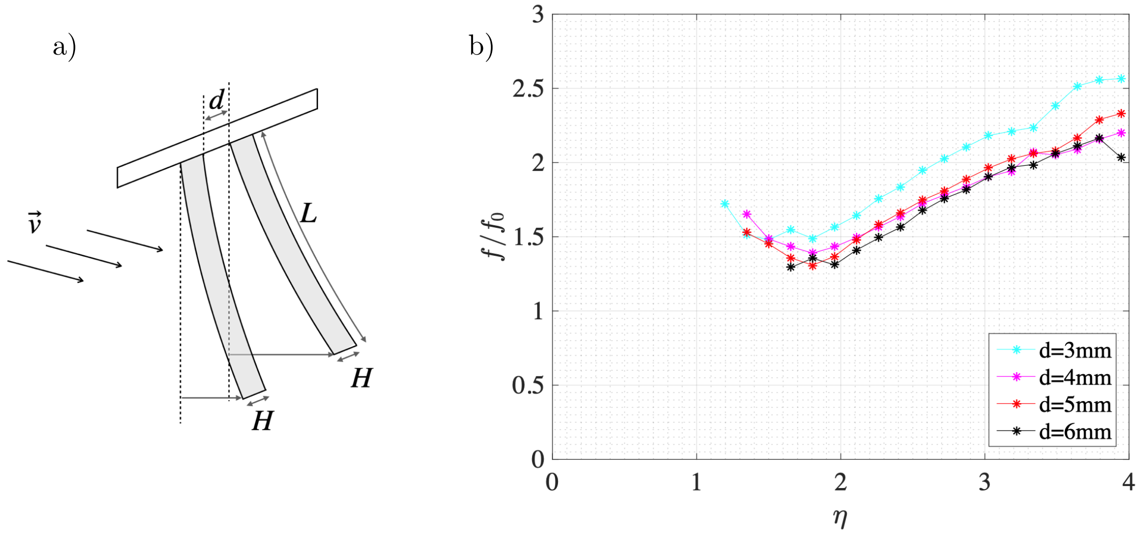

Figure 1: a) Scheme of the experimental device. b) Nondimensional plates' oscillation frequency f/f_0 as a function of the nondimensional velocity η. Here f_0 is the plate natural frequency and $\eta = v\sqrt{\dfrac{\rho H L^3}{2EI}}$ is the Cauchy number.

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Flexible foil dynamics under shear flow: stabilization through spanwise modulation.

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We study the interaction between a spanwise uniform flexible sheet (a common paper sheet) and the shear flow at the exit of a wind tunnel.

First, we characterize the coupled dynamics of elasticity and shear instabilities by analyzing the sheet's deformations and vibrations, which are linked to Kelvin-Helmholtz-type flow structures. Figure 1a illustrates this regime, combining a schematic of the boundary layer flow with synchronized photographs of the sheet's profile motion.

To capture full-field deformation measurements, we employ fringe projection profilometry (Cobelli et al. (2009)). Figure 1b demonstrates the technique's capabilities by presenting an instantaneous 3D reconstruction of the vibrating sheet.

The system exhibits bi-stability, transitioning between straight and flapping states, a behavior well-documented for flags and flexible sheets in uniform flows (e.g., Alben and Shelley (2008); Zhang et al. (2000)). However, unlike these canonical studies, our shear-layer configuration introduces a velocity gradient that couples Kelvin-Helmholtz-type vorticity with the sheet's elastic deformations. This coupling alters instability thresholds and generates distinct flow-structure interaction patterns.

Finally, we explore flow control via geometric modifications, introducing spanwise cuts in the sheet. Figure 1c presents the experimental setup for this case, showing the modified sheet illuminated with projection patterns at the wind tunnel exit. This configuration enables us to examine how strategic geometric alterations of the trailing edge affect the stability and dynamics of the fluid-structure interaction.

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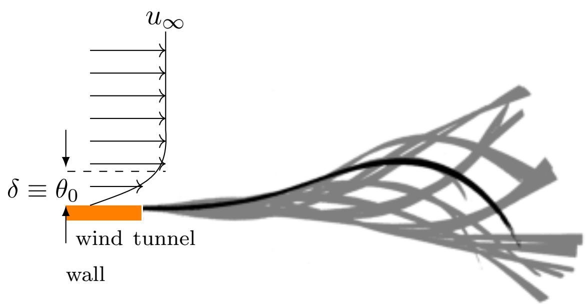
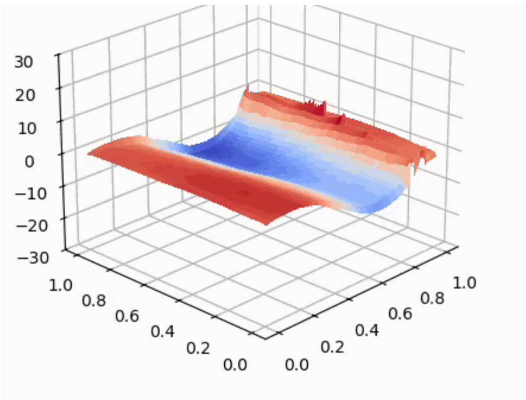
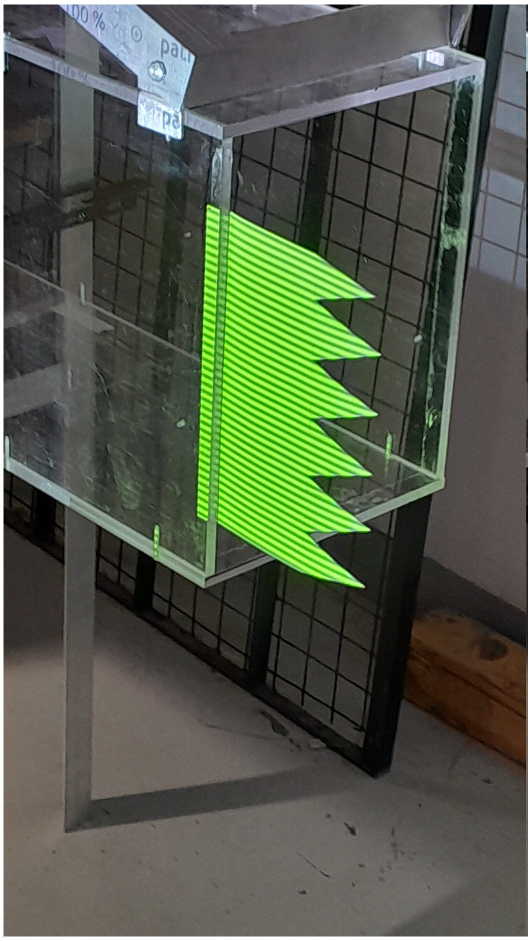


(a) 2D schematic of the experimental setup. Actual photographs are superimposed illustrating the dyamics. Momentum thickness θ_0 for the shear flow at the output of the wind tunnel.



(b) Three-dimensional foil reconstruction obtained through optical profilometry.



(c) Experimental configuration showing the modified sheet with projection patterns for profilometry.

Figure 1: Experimental setup and measurement techniques

The effect of degrees-of-freedom on self-adaptive flaps for 3D blunt body drag reduction

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The aerodynamic drag of three-dimensional blunt bodies, which model common heavy vehicles, significantly impacts transport industry energy consumption. In this study, we experimentally investigate the use of passive self-adaptive elastic flaps, inspired in the reconfiguration of flexible parts such as leaves and trees (de Langre, E. , 2008), to decrease the drag of a square-back Ahmed body (B) by interacting with its turbulent wake. Experiments were conducted in a wind tunnel at a Reynolds number $Re \simeq 2 \cdot 10^5$ to analyse the aerodynamic performance under different flap configurations attached to the body base (see Fig. 1a), including rigid (RF) and flexibly-hinged flaps with bending motion (1 Degree of freedom, 1HF) and both bending and torsional motions (2 degrees of freedom, 2HF). The fluid-structure interaction (FSI) coupling between the wake and the elastic flaps, through steady passive reconfiguration and mild vibrations, modifies the wake structure (see Fig. 1b), suppresses reflectional symmetry breaking (RSB) mode, and recovers base pressure, achieving drag reduction (see Fig. 1c) under varying flow conditions. The 2HF system outperforms the 1HF elastic flaps through its adaptation to three-dimensional wake structures that appear under yaw. Considering that crosswinds are a common but often overlooked factor in road vehicle aerodynamics, these findings provide insights into the design of bio-inspired flow control devices for separated flows in real-world transportation applications.

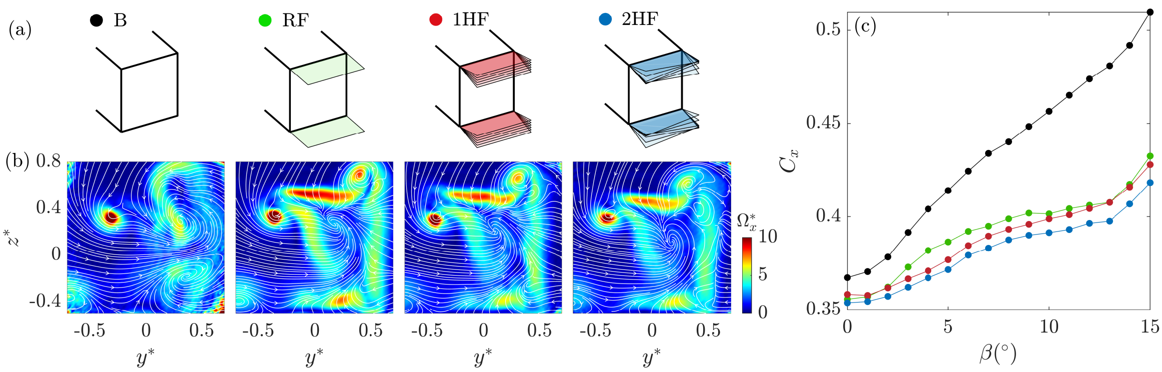

Figure 1: (a) Studied configurations (b) Contours of streamwise vorticity, Ω_x^*, and flow streamlines (U_y^*, U_z^*) represented by white lines at $x^* = 0.915$ and $\beta = 15°$ for the different configurations (c) Drag coefficient C_x evolution versus yaw angle β.

References

de Langre, E. (2008). Effects of wind on plants. Annu. Rev. Fluid Mech., 40(1), 141-168.