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On the role of physiology and kinematics of biological swimmers to spread and suppress their odors in the wake

Maham Kamran[1], Chengyu Li[2], Muhammad Saif Ullah Khalid[1*]
[1]Nature-Inspired Engineering Research Lab (NIERL), Department of Mechanical & Mechatronics Engineering, Lakehead University, Thunder Bay, ON P7B5E1, Canada
[2]Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland, OH 44106, USA
*Corresponding Author, Email: mkhalid7@lakeheadu.ca

Abstract

Underwater sensing in fish relies on the detection and processing of chemical cues dispersed in their dynamic aquatic environment. The interplay between swimmer kinematics and fluid dynamics plays a crucial role in shaping the dispersion and suppression of these chemical cues. Using three-dimensional (3D) computational fluid dynamics (CFD) simulations with an in-house sharp-interface Immersed-Boundary Method (IBM) solver, this study examines Fluid-Structure-Chemical Interaction (FSCI). Two distinct kinematic modes, carangiform (Jackfish) and anguilliform (Eel), are analyzed under transitional flow conditions at Reynold number Re = 3000 and varying Strouhal numbers (f* = 0.25 and 0.40). Q-criterion visualization is used to capture three-dimensional vortex structures, while odor concentration isosurfaces at C* = 0.5 are analyzed, considering the swimmer's body as the odor source. The results reveal that odor plumes are not only passively transported but are shaped by vortex structures. The Eel, with full-body undulation, generates stronger and more elongated odor plumes compared to the Jackfish, where undulation is localized to the posterior region. By quantifying odor effectiveness (C*eff) in the wake, it is shown that kinematics plays a more dominant role than physiology in determining odor transport efficiency. Additional simulations with variations in undulation amplitude demonstrate that increasing undulation intensity significantly enhances odor transport by increasing momentum transfer to the surrounding fluid. Further analysis of the advection-diffusion equation highlights the relative contributions of convection and diffusion in odor transport. Convection is found to dominate over diffusion due to the high Schmidt number in water, leading to greater odor dispersion at higher undulation amplitudes. These findings provide novel insights into how fish locomotion influences chemical cue transport, offering a better understanding of underwater sensory mechanisms. Understanding these mechanisms can inform the development of bio-inspired underwater robots with enhanced sensory and propulsion capabilities for navigation, environmental monitoring, and marine exploration.