ME – PhD Thesis Defense

Self-Propulsion in Oscillating Airfoils

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ABSTRACT

Self-propelled oscillating foils provide a simple and effective model system from which one can gain valuable insights into the mechanics of fish propulsion. This understanding is crucial for designing efficient propulsion systems, especially for long-distance cruising. Here, we consider two airfoil (NACA0015 section) models – rigid and composite (rigid airfoil with a flexible flap) – to assess the fundamental aspects of self-propulsion through experimentation. By studying the self-propulsion and wake characteristics across a wide range of parameters for both models, we attempt to answer a crucial and fundamental question: how are the swimming speed and efficiency influenced by imposed kinematics such as frequency, amplitude, and pitching point location? Moreover, what is the role of flexibility in fish swimming?

To achieve self-propulsion, we designed and built a novel apparatus in which an airfoil can propel unconstrained along its longitudinal direction. It utilises a long, freely rotating arm – a carbon-fibre truss – supported by air bearings on one end and houses the airfoil on the other. A spiral-spring-based crank rocker mechanism is employed for long-distance sinusoidal actuation of the airfoil. We use 2D planar Laser-Induced Fluorescence (LIF) and Particle Image Velocimetry (PIV) to capture flow patterns and the wake velocity fields in the mid-plane of the airfoils. We introduce a wake energy coefficient (C_{WE}) to quantify the energetic efficiency during self-propulsion. C_{WE} is essentially the normalised kinetic energy flux in the wake and is a measure of the work done as well as the energy wasted in the wake.

For rigid airfoils, three distinct propulsion regimes are identified, each characterised by a specific relationship between the self-propulsion Reynolds number and the imposed kinematics. Each of these relations highlights the different ways in which the pitching frequency, amplitude and location affect the self-propulsion speed. The wake of a rigid airfoil is also characterised by a wide jet-like profile, which bifurcates into two smaller jets downstream. Before bifurcation, distinct vortex shedding patterns are observed, which depend on the self-propulsion speed and pitching amplitude – parameters that determine the longitudinal and lateral separation between the shed vortices. Self-propulsion speed and efficiency increase as the pitching point moves closer to the leading edge.

In the composite foil, the effect of flexibility is more pronounced for low amplitude pitching where the self-propulsion speeds are larger than the rigid counterpart. For moderate and higher amplitudes, the introduction of flexibility does not appreciably change the speed of propulsion. However, the inclusion of flexibility appreciably alters the wake characteristics across all the parameters. The wake of the composite airfoil is narrower and has two-dimensional features. The inclusion of flexibility suppresses the wake bifurcation, with the passive bending of the flap directing the momentum and energy along the direction of propulsion, resulting in more efficient propulsion. We propose that the modification of the vorticity shedding process as a consequence of passive bending of flap leads to efficient propulsion.

These findings provide valuable insights into the role of flexibility in fish swimming.

ABOUT THE SPEAKER

Rakshita Joshi is pursuing a PhD in Mechanical Engineering conducting her research in the Fluid Mechanics Lab primarily under the guidance of Prof. Jaywant Arakeri while the thesis submission was facilitated by Prof. Raghuram Govardhan. Her primary focus is experimental fluid mechanics, particularly fluid-structure interaction (FSI) and unsteady flows.