



Beyond Periodic Flapping: Adaptive Unsteady Aerodynamics in Bio-inspired Flying Robots

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Abstract

Flapping-wing flight has long inspired bio-inspired aerial robots because of its extraordinary aerodynamic efficiency and maneuverability. Although substantial progress has been achieved in understanding unsteady aerodynamic mechanisms, most existing frameworks remain centered on idealized periodic wing motions and cycle-averaged propulsion. Recent studies increasingly suggest that transient asymmetries and multi-frequency perturbations, traditionally regarded as disturbances, can actively reorganize vortex dynamics and enhance aerodynamic performance. These findings imply that biological flight may rely not solely on stable periodic propulsion, but on continuous adaptation to evolving flow environments. Here, we argue that the next paradigm of flapping-wing aerodynamics should move beyond harmonic propulsion toward adaptive unsteady flight. We discuss how perturbation-enabled control, transient vortex interactions, and fluid-mediated adaptation may reshape the development of future flapping-wing air vehicles capable of dynamically integrating with complex aerodynamic environments.

Keywords: flapping-wing air vehicles, bio-inspired flight, fluid-structure interaction, biomimetic robotics, flapping-wing aerodynamics.

1 Introduction

Flapping-wing flight represents one of the most sophisticated forms of fluid-mediated locomotion in nature. Unlike conventional fixed-wing or rotary-wing aircraft, birds and insects achieve remarkable maneuverability and efficiency through strongly coupled interactions between body motion and surrounding vortical flows. These capabilities have long inspired the development of flapping-wing air vehicles (FWAVs), particularly in low-Reynolds-number regimes where conventional aerodynamic strategies become increasingly ineffective [1].

Over the past several decades, substantial progress has been achieved in understanding the aerodynamic mechanisms underlying flapping-wing propulsion, including leading-edge vortex stabilization, wake capture, reverse von Kármán wake formation, and flexible-wing fluid-structure interactions [2, 3]. These studies established the modern framework of unsteady aerodynamic propulsion and significantly advanced the engineering realization of bio-inspired aerial systems. Nevertheless, much of contemporary flapping-wing research remains centered on idealized



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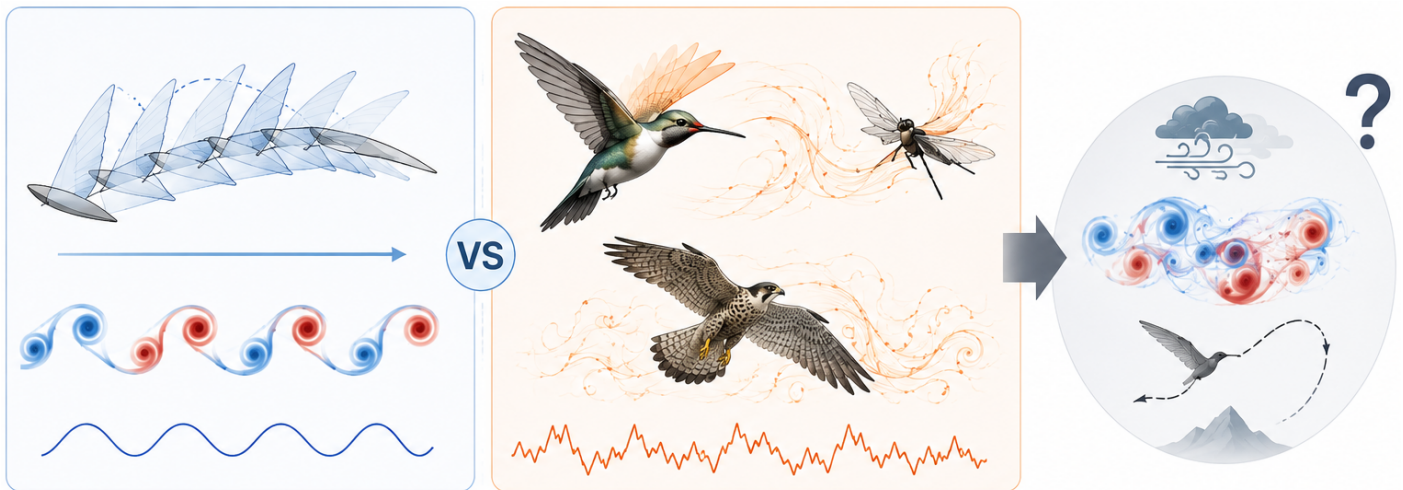


Figure 1. From periodic propulsion to adaptive unsteady flight. Classical flapping-wing aerodynamics emphasizes coherent periodic vortex shedding, whereas natural flyers operate through continuous interactions with complex and evolving flow environments. Future bio-inspired aerial systems may therefore depend on fluid-aware aerodynamic strategies beyond idealized harmonic flapping.

periodic kinematics and cycle-averaged aerodynamic performance.

Natural flight, however, is rarely perfectly periodic. Biological flyers continuously operate within complex flow environments involving turbulence, gusts, wake interactions, and rapid maneuvering demands. Consequently, their wing motions often exhibit transient asymmetries, intermittent fluctuations, and multi-scale kinematic adaptations [4], as biological flyers must continuously negotiate turbulent and unsteady flow environments [5]. Such features suggest that biological locomotion may rely on aerodynamic mechanisms extending beyond stable harmonic propulsion alone.

Recent studies increasingly indicate that non-periodic aerodynamic interactions can substantially influence vortex dynamics and force production [6–8]. These observations challenge the conventional assumption that efficient flapping propulsion necessarily emerges from coherent periodic vortex shedding.

In this Perspective, we discuss how transient aerodynamic interactions, perturbation-enabled control, and adaptive body–flow coupling may reshape the future understanding of bio-inspired flight. We argue that the next generation of FWAVs may depend less on reproducing idealized wing trajectories and more on dynamically interacting with surrounding flow structures (Figure 1).

2 Beyond Idealized Periodic Flapping

The modern framework of flapping-wing aerodynamics was largely established through canonical studies of harmonically oscillating foils in simplified freestream environments. Foundational investigations identified key mechanisms underlying unsteady propulsion, including the Knoller–Betz effect, leading-edge vortex stabilization, and reverse von Kármán wake formation [1, 9, 10]. Subsequent studies further demonstrated the importance of parameters such as the Strouhal number and wake coherence in determining aerodynamic efficiency [11]. Together, these works shaped the prevailing view that efficient flapping propulsion primarily arises from coherent periodic vortex shedding synchronized with stable oscillatory kinematics.

This paradigm has profoundly influenced both aerodynamic research and the engineering design of FWAVs. Most existing studies remain centered on approximately sinusoidal wing motions, periodic wake structures, and cycle-averaged force production [2, 12]. Within this framework, deviations from periodicity are generally interpreted as disturbances that reduce aerodynamic coherence and energetic efficiency.

Recent evidence, however, suggests that this viewpoint may be incomplete (Figure 2). Studies on flapping foils in two-dimensional flow demonstrated that transient kinematic variations can substantially reorganize wake momentum distribution and modify drag–thrust transition boundaries [6]. Moreover, reverse von Kármán wake structures traditionally

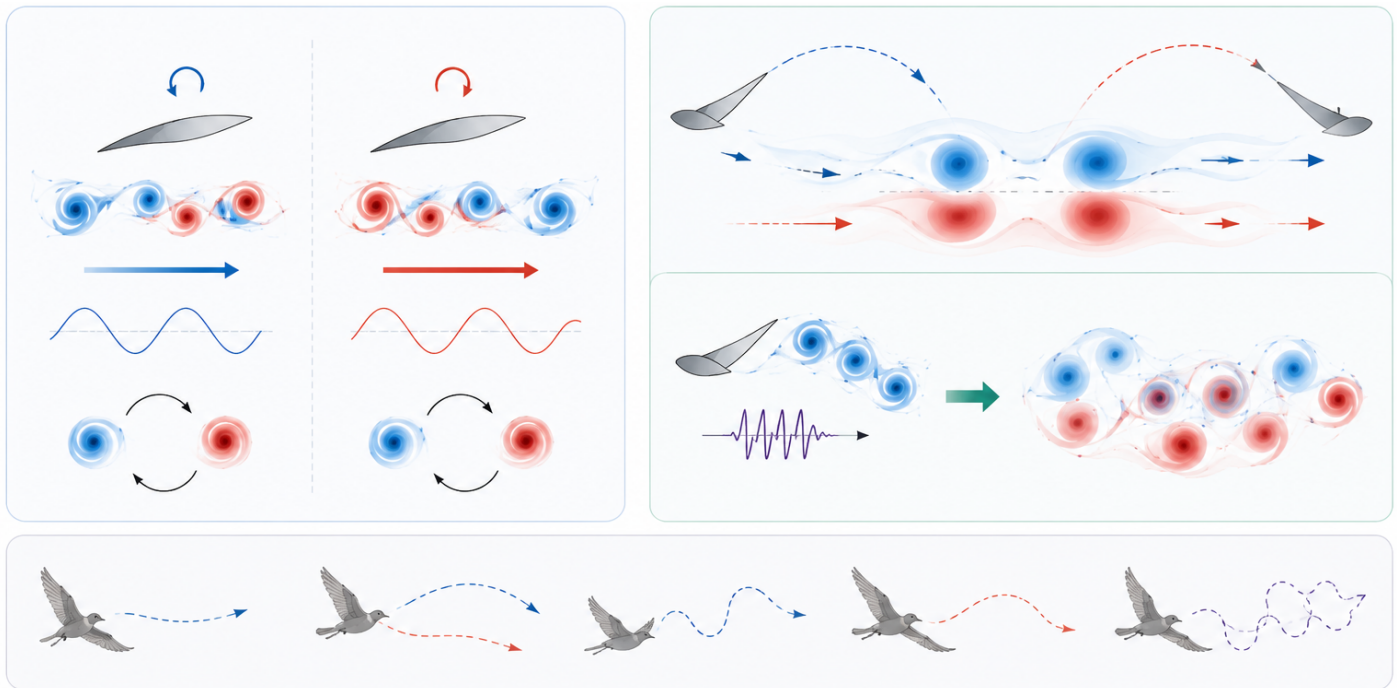


Figure 2. Recent studies suggest that transient perturbations and asymmetric vortex interactions can actively reorganize wake dynamics and modify aerodynamic performance, implying that efficient propulsion may extend beyond coherent periodic vortex shedding alone.

associated with thrust-producing states were also observed under drag-producing conditions [13], with the underlying symmetry-breaking mechanism subsequently modelled [14]. Such observations indicate that wake topology alone may not uniquely determine propulsion states, implying a more complex relationship between vortex organization and aerodynamic performance than classical periodic theories suggest.

A similar shift is emerging from recent studies on perturbation-enhanced propulsion. High-frequency perturbations superimposed onto canonical oscillatory motions were found to improve thrust generation [7], while aerodynamic rather than resonance mechanisms were shown to underlie performance enhancement in flapping-wing systems [8]. Rather than simply disrupting coherent wake formation, these perturbations can actively modify vortex interactions and transient aerodynamic loading.

From a broader fluid-mechanical perspective, these findings suggest that efficient locomotion may not rely solely on stable periodic vortex shedding. Instead, aerodynamic performance may critically depend on how body motion interacts with dynamically evolving flow structures across multiple temporal and spatial scales.

This emerging evidence motivates a reconsideration of

how bio-inspired flight should be understood. Rather than viewing aerodynamic irregularity purely as a deviation from optimal locomotion, future studies may need to consider whether transient flow interactions themselves constitute an essential component of biological propulsion.

3 Adaptive Perturbations as an Aerodynamic Control Dimension

An important implication of recent perturbation-enhanced propulsion studies is that aerodynamic irregularities may constitute a functional control mechanism rather than merely a source of instability. Conventional flapping-wing systems typically seek stable and repeatable kinematics in order to maintain predictable aerodynamic performance. Under such a framework, perturbations are generally treated as disturbances that should be minimized or rejected.

Recent findings increasingly challenge this assumption. High-frequency perturbations superimposed onto canonical oscillatory motions were shown to enhance thrust generation and alter aerodynamic loading conditions [7, 8, 15]. These effects suggest that perturbations can actively regulate vortex interactions rather than simply disrupt them.

Importantly, the aerodynamic influence of

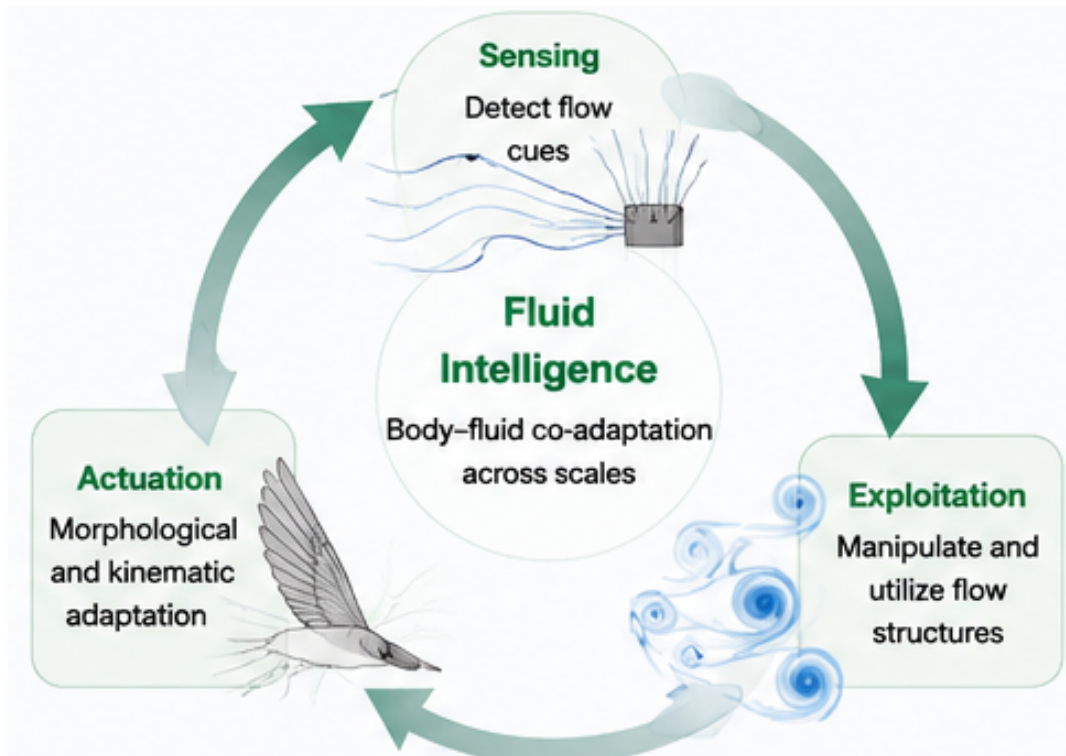


Figure 3. Conceptual framework of biologically inspired fluid intelligence in flapping-wing flight systems. Through the closed-loop interplay of sensing, exploitation, and actuation, natural and bio-inspired flyers continuously detect environmental flow cues, manipulate surrounding vortical structures, and adapt their morphology and kinematics to achieve robust body–fluid co-adaptation across multiple spatial and temporal scales.

perturbations appears to depend strongly on transient synchronization between body motion and surrounding flow structures. Under such conditions, aerodynamic performance may be governed not only by mean kinematics, but also by the timing and organization of local vortex interactions. This viewpoint extends classical propulsion theories beyond purely cycle-averaged momentum transfer toward dynamically coupled body–flow regulation.

From a broader perspective, adaptive perturbations may provide biological systems with an additional degree of aerodynamic freedom for modulating thrust, maneuverability, and energetic efficiency in rapidly changing environments. Rather than relying exclusively on predefined harmonic trajectories, biological flyers may continuously adjust local flow interactions through transient kinematic modulation across multiple scales.

Such a possibility carries important implications for future FWAVs. Existing robotic systems remain largely dependent on deterministic actuation strategies built upon prescribed wing motions. Future flapping-wing systems, however, may increasingly require control architectures capable of strategically generating and regulating perturbations in order to manipulate

surrounding vortex dynamics in real time.

Under this emerging framework, perturbations are no longer secondary corrections to periodic propulsion. Instead, they may represent a previously underexplored aerodynamic control dimension underlying the robustness and adaptability of biological flight.

4 Toward Fluid Intelligence in Bio-Inspired Flight

The emerging role of adaptive aerodynamic interactions suggests a broader conceptual shift in how bio-inspired flight should be understood. Classical aerodynamic frameworks generally treat the surrounding fluid as a passive medium through which forces are generated. Biological flight, however, appears to rely on a more deeply coupled relationship between body motion and evolving flow structures.

This perspective motivates the concept of *fluid intelligence*. Here, fluid intelligence does not refer to intelligence in the conventional computational sense, but rather to the capacity of biological systems to continuously exploit surrounding flow dynamics through coupled morphological, kinematic,

and sensory adaptation (Figure 3). Under this framework, vortices are no longer merely wake signatures generated by locomotion, but dynamic flow structures that may participate directly in propulsion, sensing, and control.

Several emerging directions in bio-inspired flight already point toward such a paradigm. Flexible wings introduce passive fluid–structure coupling that enables local aerodynamic adaptation to changing loading conditions [2, 4]. Similarly, distributed airflow sensing observed in birds and insects suggests that biological systems may integrate sensing and actuation directly through body–flow interactions rather than through isolated control architectures.

Recent developments in embodied intelligence and morphology-centered robotics further reinforce this viewpoint. Increasing evidence suggests that efficient locomotion may depend not solely on prescribed kinematics, but on the continuous ability of biological systems to coordinate with surrounding flow structures across multiple scales.

Such a shift carries important implications for future FWAVs. Existing robotic systems remain largely dependent on deterministic control strategies and predefined wing trajectories. Future bio-inspired aerial robots, however, may increasingly require fluid-aware control architectures capable of dynamically interacting with surrounding vortex structures through adaptive resonance, distributed sensing, and morphology-mediated aerodynamic regulation.

Under this emerging framework, the long-standing objective of reproducing biological wingbeats may itself become insufficient. The future challenge may instead lie in understanding how living systems integrate fluid dynamics into the control process itself. In this sense, the next generation of bio-inspired flight may evolve from mechanically mimicking nature toward dynamically coexisting with the surrounding fluid environment.

5 Conclusion

For decades, the development of flapping-wing aerodynamics has largely been guided by the pursuit of stable periodic propulsion. While this framework established the foundation of modern unsteady aerodynamic theory, growing evidence suggests that biological flight may rely on far more dynamic interactions with the surrounding fluid environment.

This emerging viewpoint motivates a broader

reconsideration of bio-inspired flight. Future progress may depend less on reproducing idealized wing trajectories and more on understanding how living systems continuously coordinate with evolving flow structures through coupled body–fluid interactions.

Such a transition may ultimately redefine the objective of bio-inspired aerodynamics itself. Rather than treating the fluid merely as a medium for force generation, future flapping-wing systems may increasingly exploit surrounding flow structures as active components of sensing, control, and locomotion. The next generation of FWAVs may therefore evolve beyond mechanically efficient flying machines toward fluid-aware systems capable of dynamically integrating with complex aerodynamic environments [16].

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Conflicts of Interest

The author declares no conflicts of interest.

AI Use Statement

The author declares that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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