Abstract

Locomotion is necessary for survival of living systems. Among them, aerial and aquatic flapping systems have high energy expense due to repetitive motion of wings or fins against the ambient fluid. The benefit is gain in circulation due to rapid flow separation which sheds rotational energy in the wake.

Inter-specific phenomenological observations show that there is a wide spectrum of maneuvers to attain locomotion. So far, science relies on morphology, physiology and kinematics for explanations. Whether there exists a set of unifying physical mechanisms based on fluid mechanics alone is the motivation of the present thesis.

Here, the objective is to investigate available energy in the wakes of individual and collective flapping flight. The emphasis lies on physical justifications, may even be hypothetical, for three-dimensional (3D) real-life and computational observations. To this end, the study examines momentum-based transport phenomena for three categories of simple incompressible models.

First, there are two-dimensional (2D) flow fields of six engineered models where they flap in hover mode at certain wingbeat frequencies ($1.5\,Hz$ and $2\,Hz$), and vary in aspect ratio (1.5 and 1.0) and use of winglet. Data were recorded at the mid-chord plane using particle image velocimetry in quiescent water during the doctoral study of a fellow researcher. The flapping motion is one-sided without the body, and asymmetric in time (stroke duration) and space (stroke angle relative to a reference). The chord-based Reynolds number is of $\mathcal{O}(10^4)$.

Comparative analysis of the six cases enables the dynamical interpretation of observations, such as: higher pressure gradient along the leading edge vortex (LEV) of hawkmoths as compared to fruitflies does not necessarily induce span-wise flow in the LEV; LEVs of hawkmoths inflect toward wingtip earlier than other insects; hawkmoths and bats use vortex loops for thrust; role of kinematics and wake energetics in the change of camber to control LEVs; and the fore-wing/hind-wing phase difference and inconsistent span-wise flow in dragonflies.

Second, a generalized unsteady 3D viscous model of purely helical flow shows

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that there is self-sustained energy in the wake which is available for extraction by flapping wings. The unsteady model parameters evolve according to the unforced Navier-Stokes (N-S) equations of motion. The model's nonlinearity is essential to capture the phenomenon. The analysis provides a probable physical explanation for superior efficiency of bumblebees over orchid bees. Interdisciplinary applications include dynamic modeling in superfluid turbulence and magneto-fluid dynamic dynamo theory.

Third, transport in a 2D modeled dipolar double gyre wake illustrates that V-shaped formation in flapping flight is a stable response to mechanistic signal transmission through wakes. The 2D model makes sense because the time a bird spends in the wake of its leader is so less that it cannot recognize the three-dimensionality of the wake itself. The present work has implications in bio-inspired design and the solution of dilemma in cooperative formation flight. The study further explains that wake dynamics is useful in tackling complex formations, such as flocks of pigeons.

The study of these models shows that the Lamb vector (cross product of vorticity and velocity), its divergence and the fluid dynamic current vector are fundamental quantities. They have their analogies in the Maxwell's equations of electromagnetism when the N-S equations are presented as the vorticity-Lamb vector formulation. Transport phenomena for an ensemble of variables – velocity, vorticity, kinetic energy, enstrophy, flexion product and the Lamb vector divergence – provide a holistic understanding of wake energetics. In particular, substantial enstrophy transport shows that positive diffusion is an essential mechanism in infusing rotationality in the wake. Other tools such as dispersion radius, finite-time Lyapunov exponent and dimensionality reduction with principal components analysis and dynamic mode decomposition highlight the finer details.

Keywords: flapping flight, helical wake, dipolar wake, V-formation, transport phenomena, positive diffusion, dimensionality reduction

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