The aerodynamics of a dragonfly

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Dragonflies, belonging to the Infraorder Anisoptera, are renowned for their exceptional flight capabilities such as rapid acceleration, backward flight, and the ability to hover. They can produce aerodynamic lift up to 4.3 times their body weight. Much of this is due to a phase difference between the forewing and the hindwing. Dragonflies employ a direct flight mechanism, in which the muscles are attached directly to the wings' bases, allowing precise control over wings' movements. This means that the dragonfly has independent control of each wing, which it controls to its needs among the many flight modes a dragonfly can perform. The dragonfly can switch flight modes without altering postures and has the most stable hovering capability of all insects. [1] The phasing of hindwings does not create an advantage in terms of lift force but rather recovers energy from the wake wasted as swirl in a manner analogous to coaxial contra-rotating helicopter rotors. This greatly improves efficiency, decreasing lift requirements by up to 22% compared with a single pair of wings. [2]

The special shape of the dragonfly wing also contributes to their flying abilities. Dragonfly wings are corrugated and the corrugation increases the wings' stiffness-to-weight ratio and influences airflow patterns during flapping. Compared to the flat wing, where secondary vortex with a sign opposite to that of the leading-edge vortex, a spiraling airflow pattern that forms along the leading edge of the wing during the downstroke, develops and erupts to discourage lift enhancement, corrugated wings suppress such an eruption of the leading-edge vortex with the corrugation structure, which enhances the lift. [3] This is important as dragonflies fly at ranges from Reynolds' number 2,000 to 8,000. The Reynolds number (Re) is a dimensionless quantity used in fluid mechanics to predict flow patterns in different fluid flow situations. It is defined as:

$$Re = \frac{\rho v L}{\mu}$$

where ρ is the fluid density, v is the characteristic velocity, L is the characteristic length (such as chord length of the wing), and μ is the dynamic viscosity of the fluid. This Re range indicates that dragonflies operate in a regime where both viscous and inertial forces significantly influence aerodynamic performance. [4] The corrugated wing could provide a fixed separation point which leads to a decrease in drag which the flat wing suffers from whilst also increasing lift. These specially designed aerodynamic features mean that the dragonfly can fly at around 100 body-lengths per second, and backwards at about 3 body-lengths per second. They can also hover for around a minute, but they do not hover for longer as stagnant flight disturbs thermoregulation. [5]

Another intricate detail of nature is that dragonfly wings have a dense, intricate lattice of veins that serve as the backbone for the wing membrane. These veins compartmentalize the wing into multiple areas, each capable of independent flexion, which further increases the aerodynamic efficiency. [6]. By thickening the membrane where stress is most pronounced and thinning the membrane where less stress is experienced, the venation pattern helps mitigate localized buckling and reduces the overall mass required to maintain structural stiffness. The junctions between veins also act like hinges, which allows bending at the dragonfly's control without compromising the wing's integrity, while the thickened nodal areas absorb stress during manoeuvrers such as acceleration or sudden changes in flight path which can be up to 4G and 9G respectively. Near the wing-tip the pseudostigma, which is a small pigmented area bound by specialized veins, adds concentrated mass that shifts the natural frequency of the wing, helping to dampen vibrations and suppress flutter at high flapping frequencies [7]. This helps the wing shedding to avoid the domininant frequency which can cause structural deformation and this vibration dampening ability is key for the dragonfly's flight stability, especially during hovering.

The unique structure of dragonfly wings have led to various biomimetic applications, particularly in the field of airfoil development. Researchers have explored the incorporation of dragonfly-inspired designs into aircraft wings to enhance performance. For example, a study applied dragonfly wings patterns to a scaled model of a Boeing 777 wing and observed a significant improvement in structural efficiency. The dragonfly-inspired design improved the out-of-plane stiffness by approximately 25%, suggesting the potential to develop lighter and more efficient wing structures. [8] Further, the tandem wing configuration of dragonflies is being considered for its potential use in micro-aerial vehicles. Copying the interaction between forewings and hindwings in dragonflies could lead to micro-aerial vehicles with improved aerodynamic efficiency and manoeuvrability. [9]

In conclusion the aerodynamics of a dragonfly offers valuable insights into the complexity of nature and how we can adapt our machines from it. The unique wing structures, made of corrugated sections and intricate vein design, of dragonflies enable their extraordinary flight capabilities. Their wings lead to advancements in aircraft efficiency and the development of agile micro-aerial vehicles and definitely much more in the future.

References

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