A review on insects flight aerodynamics, noise sources, and flow control mechanisms

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Abstract

Wildlife always acts as an inspiration source for humans to help them study and mimic flight methods. Insects are one of the most important sources of biological systems' inspiration to control flow and reduce aerodynamic noise. Insects are classified into different kinds, and most can fly by fluttering their wings. In general, insects' flight muscles are divided into direct and indirect types that act synchronously and asynchronously with nerve impulses, respectively. These muscles help insects use a mixture of rotating, flapping, and pitching movements to achieve specific wing kinematics. Insects use various mechanisms for generating aerodynamic forces, including the Weis-Fogh or clap and fling mechanism, delayed stall due to unsteady motion (Wagner effect), wing rotation (Kramer effect), wake capture or wing–wake interaction, added mass, and absence of stall. On the other hand, the insect noises are divided into aerodynamic and structural. Insects' aerodynamic noise is created by fluctuating forces, flow–solid interaction, shed vortex, and turbulence inflow. Meanwhile, insects' structural noise is made by frictional and tymbal mechanisms. Their flow control methods are classified into two categories: wing shape and sub-structures. Wing shape features such as planform, chord length and location, twist, sweep, wingtip, and aspect ratio influence the flow around the insects. The sub-structures such as leading edge, trailing edge, swallowtail, and surface textures affect the flow too. A thorough understanding of insects' fly, aerodynamic noise, and their control flow techniques will significantly help engineers to produce competitive products with better aerodynamic performance and aeroacoustic signature.

Keywords

Insects, aerodynamics, flight mechanisms, noise, flow control

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Introduction

Wildlife always acts as an inspiration source for humans to help them study and mimic flight methods.[1,2] By examining the structure and function of biological systems, patterns can be found to develop new technologies and innovations to solve complex human problems.[3] Nowadays, aerodynamic noise has become a significant problem since aircraft and rotorcrafts are used in large numbers.[4] Aerodynamic noise is the sound produced by fluid flows or the interaction of fluid flow with solid boundaries. Noise has adverse effects on humans' and animals' health, such as fatigue, mental illness, cognitive dysfunction, aggression, hormonal disorders, stress, stroke, heart attack, hypertension, diabetes, sleep disruption, and hearing impairment.[5] Therefore, low-noise products are more competitive in the market, and aerodynamic and acoustic improvements are critical to increasing operational duration and lowering noise. To reduce aerodynamic noise, there is a need for creative methods to control the flow and eliminate the factors that produce the sound.

Insects are one of the most important sources of biological systems' inspiration to control flow and reduce aerodynamic noise, especially while applying passive control techniques. Passive techniques control the flow by making small changes in the geometry or adding substructures to the surface.[6] To draw inspiration from insects, we must first understand how they create aerodynamic forces and then acknowledge the authority of pressure perturbation and turbulence flow as noise sources. Finally, we want to understand how they manage this turbulent flow so that we may apply these strategies to our industrial

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applications. As a result, this research aims to look at how insects fly, identify aerodynamic noise, and understand how they control flow and noise.

With growing concern over developing MAVs (Micro Air Vehicles) and UAVs (Unmanned Aerial Vehicles), insect flight aerodynamics have been studied in order to gain insight into their unsteady force generation mechanisms.[7–12] Misof et al.[13] showed that insects are classified into different kinds, and most can fly by fluttering their wings (Figure 1). Insects have different species, fly slower than birds, and operate at low Reynolds number flows. When a fluid passes through another, two forces are created: the viscous force, which is the force of the first fluid to move through the second one, and the

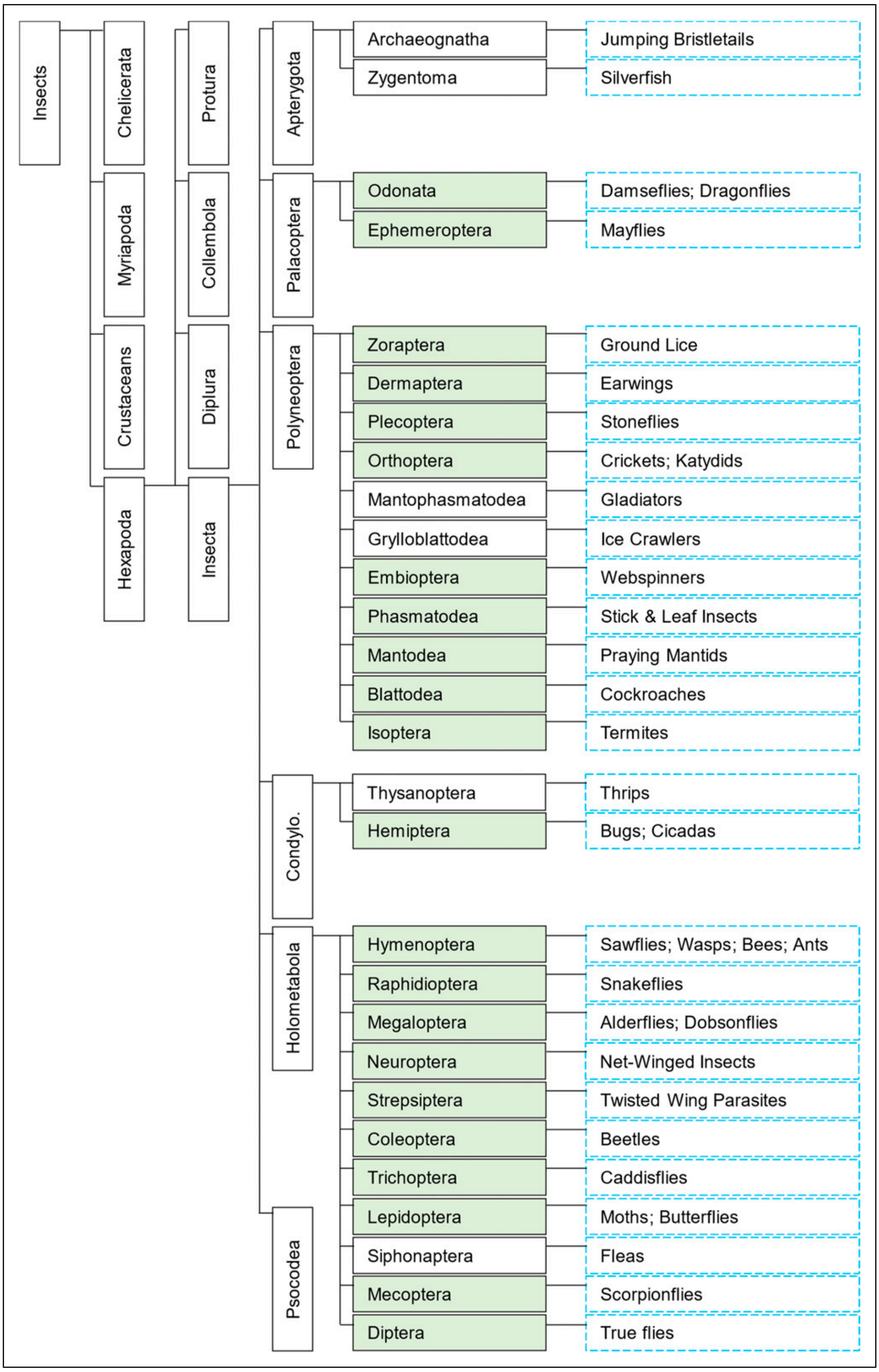

Figure 1. Classification of different kinds of insects.

inertial force, which is the resistance of the second fluid to the force of the first fluid. The ratio of these two forces is a dimensionless number known as the Reynolds number. By reducing the size of birds and insects, the Reynolds number decreases due to the small size of the wings. Because insects fly at a slower speed and with a lower Reynolds number than birds, they must flap at a greater frequency and quicker than their bodies can respond.[14] Table 1 shows the fluttering frequency for different insects. It is evident that as the size decreases, the fluttering frequency increases to produce adequate lift to keep its weight in the air using smaller wings.[15]

Flight mechanisms and aerodynamics of insects

Insects have developed gradually over millions of years to deal with complex challenges, so some unique properties have helped them survive.[16] In general, insects' flight muscles are divided into direct and indirect (Figure 2). Direct flight muscles attach directly to the wings and act synchronously with the nerve impulse. On the other hand, indirect flight muscles deform in the chest and act asynchronously with nerve impulses. The mechanical energy from the muscles' contraction and expansion vibrates the wings at the optimal frequency, and insects fly.[17,18]

For flight, insects open their wings and push them down. The wings rotate at the end of the downstroke, pull up, and rotate again to push air down. This procedure is repeated at a high frequency to generate the required forces for flight (Figure 3(a)). There are different flight patterns in insects. The wing movement can generally be expressed in the X, Y, and Z axes (Figure 3(b)). Through wing rotation around the Y-axis, the forward–backward motion emerges which is known as rotating. Also, rotation around the X-axis creates an up–down motion called flapping. Eventually, rotation around the Z-axis changes the angle of attack, known as pitching. These three actions are used by the insects to create distinct wing kinematics and shape their best flying mechanics.

Table 1. Insects flapping frequency.[15]

Insect	Wing size (mm)	Frequency (Hz)
Butterflies	42.7–57.3	4–10
Damselfly	18–190	15–20
Dragonfly	50–127	25–40
Beetles	14–25	40–90
Honeybee	9.7	200
Mosquito	2.4–3.3	450–600
Midges	1–3	600–1000

Insects use various mechanisms for generating aerodynamic forces, including the Weis-Fogh or clap and fling mechanism, delayed stall due to unsteady motion (Wagner effect), wing rotation (Kramer effect), wake capture or wing–wake interaction, added mass, and absence of stall (Figure 3(c)). Generally, these mechanisms for generating aerodynamic force use phenomena such as rotational drag or trailing edge vortex to aid in flapping at high frequencies[19–23] which will be further described below.

Added mass

By increasing or decreasing the acceleration of the wing, pressure is exerted on the wing in reverse motion. This pressure, known as added mass, is felt by the wing structure and muscles and is typically modeled mathematically as a time-variant increase in inertia. The added inertia increases the forces associated with wing

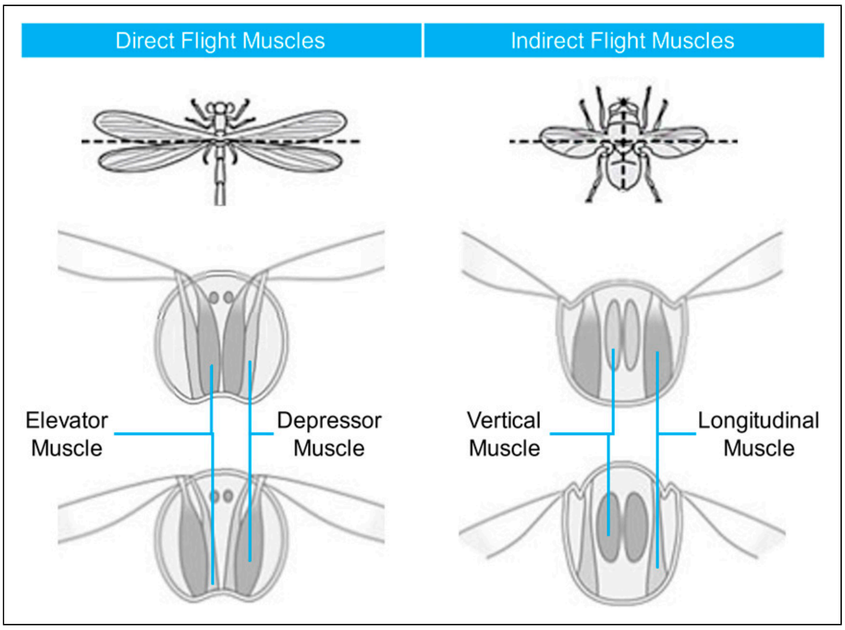

Figure 2. Mechanism of insect muscles during flight.[18]

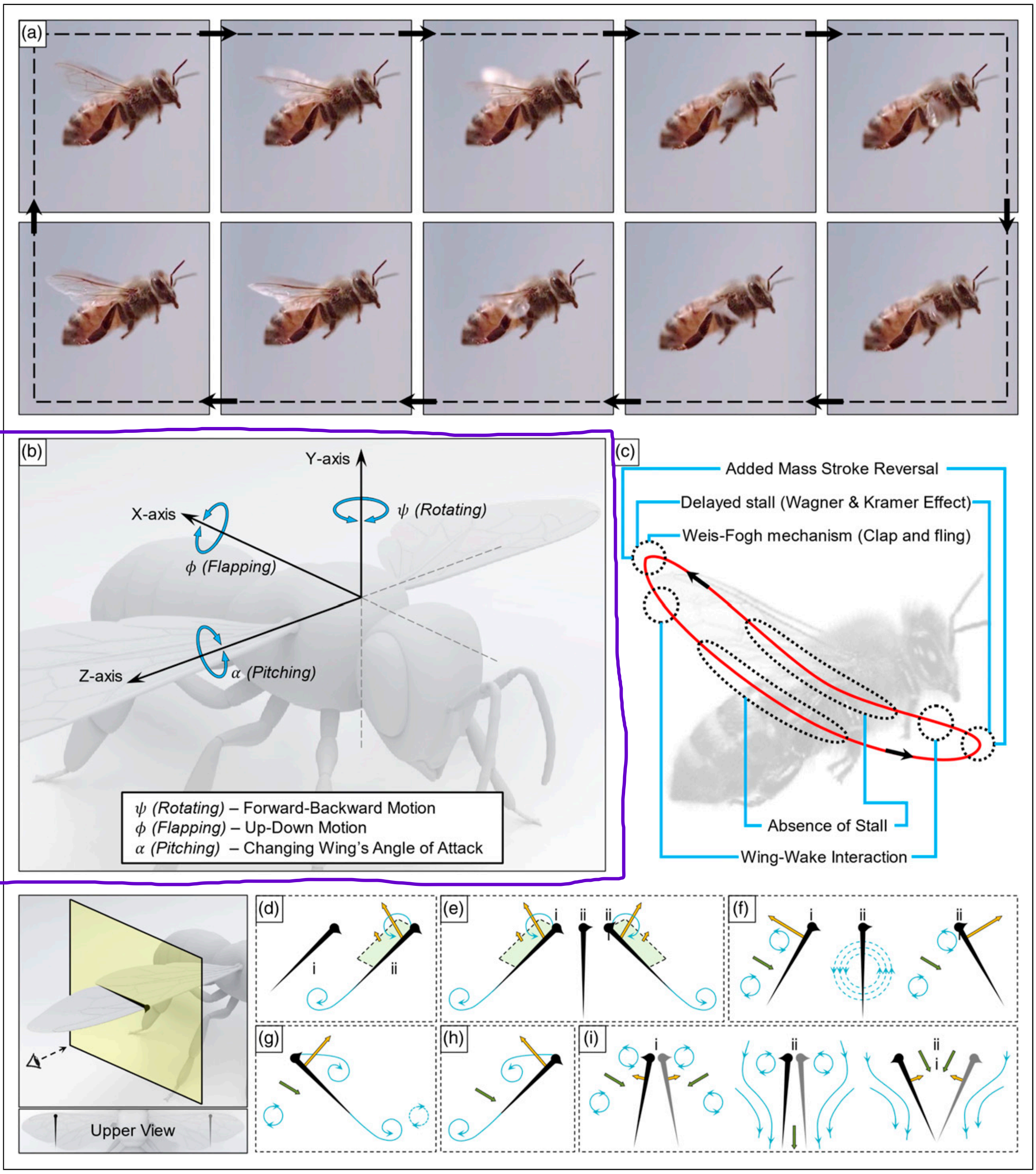

Figure 3. (a) Represents a full cycle of conventional insects' wing fluttering; (b) insect's wing motions; (c) mechanisms for generating aerodynamic forces; (d) added mass (at start); (e) added mass stroke reversal; (f) delayed stall (Wagner and Kramer effect); (g) wing–wake interaction; (h) absence of stall; and (i) Weis-Fogh mechanism—rear view (blue curved arrows: flow; green arrows: induced velocity; orange arrows: net force on wing).

acceleration and thus increases aerodynamic forces[8,24,25] (Figures 3(d) and (e)).

Delayed stall due to unsteady motion (Wagner effect) and wing rotation (Kramer effect)

Delay at the beginning of stall due to sudden wing reversal is known as the Wagner effect and increased rotation as the Kramer effect. The circulation around the wing generates lift. For the airfoil at a high angle of attack, when the flow separates from the surface and stalls occur, the lift force disappears. If the airfoil is flicking or the angle of attack increases with the airfoil rotation, the stall angle increases, and the airfoil can travel longer distances before the lift disappears. In general, delayed stall leads to an increase in the lift at a high angle of attack[26–33] (Figure 3(f)).

Wake capture (wing–wake interaction)

The leading and trailing edge vortices are shed immediately after the reversal phase, creating a region behind the wing known as the wake. The wing interacts with the wake and shed vortices during flying in a group or maneuvering. These shed vortices can assist insects in increasing or decreasing lift power and spin throughout the maneuver. The wing–wake interaction hypothesis predicts that the wing continues to produce force even after a complete stop at the end of each half-phase[7] (Figure 3(g)).

Absence of stall

At a high angle of attack, the flow separates at the leading edge, and a vortex appears. The flow behind this vortex attaches to the wing surface again, and a stall does not occur. Due to the presence of this vortex and increased normal pressure force on the wing surface, drag significantly increases. However, the absence of stall during leading edge vortex stabilization is the main mechanism for boosting the lift in the middle of the flapping motion[7,8,26,34] (Figure 3(h)).

Weis-Fogh mechanism (clap and fling)

Most of the lift produced by insects using the Weis-Fogh mechanism occurs during take-off. When the wings close from behind, the air compresses backward, providing a forward force. Furthermore, by opening closed wings at the top, air enters between them, creating lift force[35–37] (Figure 3(i)).

Insects noise sources

Clark[38] reviews flyers' sound production mechanisms by focusing on their anatomical structure and wings, showing how flight sounds are generated. The insect noises are divided into aerodynamic and structural.[39] Insects' aerodynamic noise is created by fluctuating forces, flow–solid interaction, shed vortex, and turbulence inflow. Low-frequency noises are propagated by fluctuating lift and drag due to the flapping. Also, tonal noises are generated by the interaction between wings and fluid flow, known as whistles. Furthermore, the shed vortex and turbulence inflow cause atonal noises. Meanwhile, insects' structural noise is made by frictional and tymbal mechanisms. The frictional mechanisms create atonal noise in flight and tonal noise when wings slide past each other. Further, when wings swing back and forth between two conformations, tymbals and other bistable systems appear and produce impulsive and atonal noises (Figure 4).

Flow control mechanisms

Nature appears to have done an incredible job of developing insects' wings with high functionality and prolonged flight. They can float in the air, sit in small places, fly backward, land upside down, and camouflage easily. It is fascinating how such delicate appendages in their bodies can raise them into the air and perform maneuvers in different environmental conditions.[40–44] The development of wings is an important event in insects' evolutionary history and is one of the key reasons for their enormous variety and ecological success.[45] The insect flight systems' evolution is influenced by aerodynamic efficiencies, environmental conditions, food supply, the possibility of escaping from predators, the ability to attract mates, the mating process, and fracture resistance. Insects' evolution has created some flow control techniques to maximize aerodynamic performance and minimize noise.[44,46,47]

Insects generally have two pairs of wings with different types of surfaces, such as membranous, stiff, rigid, scaled, and fringed with hairs. Their appearance, color, and texture vary between insects and different species. In addition to creating aerodynamic forces, the wings are used as body temperature regulators, protective armor, communication devices, visual detection, hydrophobicity, and antibacterial activities. Studies on the insect's aerodynamic forces affected by structural parameters are an essential part of academic and non-academic research. The wing morphologies can be divided into two major parts: wing shape and sub-structures.[48–53]

Wing shape

Wing shape features such as planform, chord length and location, twist, sweep, wingtip, and aspect ratio (AR) influence the flow around the insects. The planform sets

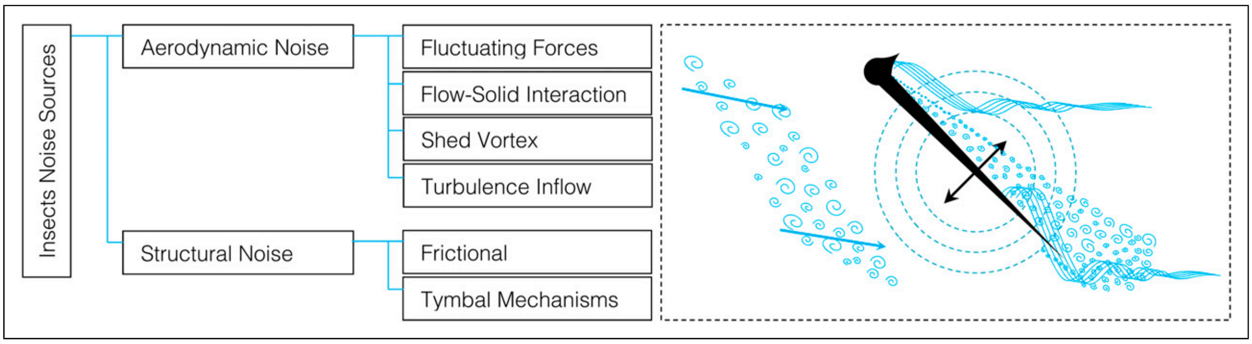

Figure 4. Insects noise sources.

the chord length and sweep angles of each wing's section and wingtip appearance (Figure 5). If the location of the longest chord on the wingspan is near the wingtip, then the generated lift would be increased. Insects' wings have concavity along the wing, and it is different in various types of insects, but most of them have a high sweep angle at the wing's tip. Furthermore, sweep impacts the aeroelastic response and loading of the wing, as well as the pressure of sound signals received from diverse noise sources. Also, the twist of the wing increases as it moves towards the wingtip and changes the radial velocity. The twisted wing has lower loading noise when the load distribution changes.

Ansari, Knowles, and Zbikowski[54] developed and used a nonlinear unsteady aerodynamic model to study hovering insect-like flapping wings. They compared the influence on several synthetic planform shapes while varying only one parameter at a time to investigate the

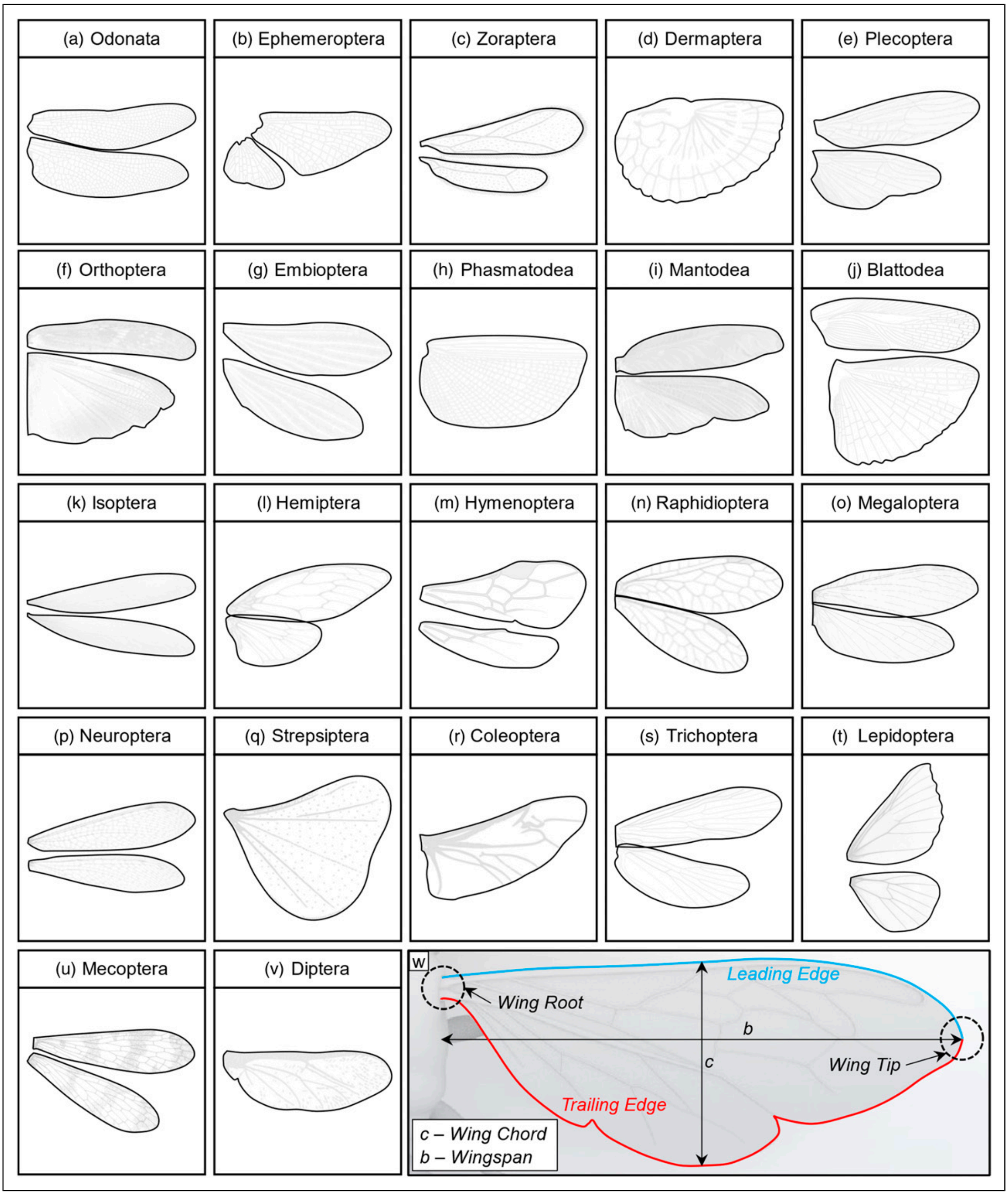

Figure 5. Schematic of flying insects wing and wing characteristics.

effects of wing geometry on the aerodynamic performance of such flapping wings. They discovered that attachment forms with virtually straight leading edges and greater area outboard, where flow velocities are higher, tend to perform best. Wang and Wu et al.[55] employed a computational fluid dynamics method to study how specific geometric parameters of the flapping rotary wing, such as the camber of the airfoil, radius of the second area moment, twist angle, and AR, affect the flow behavior, aerodynamic forces, and moments of the flapping rotary wing at various low Reynolds numbers. They discovered that maximum airfoil camber significantly influences only the rotary moment, that increasing the radius of the second area moment enhances the leading edge vortex near the tip and increases the mean lift coefficient, and that the maximum mean rotary moment coefficient was obtained when the wing planform was close to a rectangle. They also demonstrated that an excessive AR reduces lift efficiency while increasing the magnitude of the rotary moment. Meng and Sun[56] measured the wing kinematics and morphological parameters of seven freely hovering fruit flies and numerically computed the flapping wings' flows. They showed that two unsteady mechanisms are responsible for the high lift. One is called fast pitching-up rotation, and the other is the delayed stall mechanism. Ennos[57] demonstrated that high AR wings constantly improve glider flying performance, but that profile drag rises with increasing AR.

The AR of the insect wing shape, which is measured as the ratio of wing length (b) to average chord ($\overline{c}$), is one of the most important factors in determining aerodynamic performance (Figure 5(w)). Because of the variety of forms of insect wings, determining the mean chord will be difficult. As a result, the square ratio of wing length to wing area (b^2/S) is used to determine the AR, where the area of a wing may be acquired by photographing the wing. Also, in certain studies, the total area of two wings (S') is employed instead of the area of one wing (S). The AR of insect wings is in the range of $1.5 \leq AR \leq 6$. By decreasing the AR, the amount of induced drag increases. Furthermore, assuming that the chord size stays constant, by decreasing AR, the number of wing strokes increases almost exponentially. As a result, smaller insects with lower AR flap their wings more often, have lower inertia, and deform less.[14,54–61]

An experimental study shows the effects of different operating circumstances and geometric factors on six small propellers' aerodynamic and aeroacoustic performance with a distinctive planform shape inspired by five insects and one plant, such as Blattodea, Hemiptera, Hymenoptera, Neuroptera, Odonata, and maple seed.[62] The results indicate that all bioinspired propellers produce greater thrust for the same power source, reduce harmonic and broadband noise, and offer a better noise level than a conventional propeller. Furthermore, their rotational speed is lower, and their figure of merit is higher at hover flight with the same thrust as a conventional propeller.

Sub-structures

Choi et al.[63] demonstrated various successful biomimetic flow controls, which were classified into two types: (1) devices connected or added to wing surfaces for high aerodynamic performance and (2) smart surfaces for minimal skin friction. Significant flow separations are directly proportional to the decline of wing aerodynamic performance (e.g., stall). Patterns in biological structures, such as hairy microstructures at the leading edge, limit flow separation and allow fluid to stick to the surface of the wing[64] (Figure 6(a)).

The trailing edge influences aerodynamic performance, and changing it may cause the boundary layer to separate later and alter the wake structure.[65] The trailing edge of the dragonfly wing has three-dimensional ridges with edges (Figures 6(b) and (c)). When a garni-flap wing inspired by the trailing edge of a dragonfly wing is used to imitate glide flight at an angle of attack of less than 5°, it is discovered that this structure decreases drag by around 10% without affecting lift. The drag is reduced to stabilize the wake's instability by changing the wake's two-dimensional oscillations to three-dimensional oscillations[66] (Figures 6(d) and (e)).

Swallowtail butterflies' hindwings contain conspicuous tail-like protrusions. The aerodynamic function of these tails in glide flight is of particular interest to researchers. It is stated that by evaluating the flow around a rigid butterfly wing model, the hind-wing tails minimize drag by maintaining and stabilizing the tip vortices and lowering turbulence in the wake behind the wing. At an angle of attack greater than 15° ($\alpha > 15°$), the lift-to-drag ratio improves with this tail, and without this tail, the butterfly lift coefficient falls by 10%–20%, while the drag coefficient rises by roughly 5% (Figure 6(f)).[63,67–69]

Many insects' wings, particularly dragonflies', feature structures along the chord that might be perceived as roughness (Figure 6(g)). Buckholz[70] observed the uneven form of several insect wings to examine the functional relevance of spanwise wing corrugation in living systems. The results revealed a steady-state recirculation region along the model's leading edge. The separated flow region above this recirculation zone produced a laminar reattachment to the model. Following the separation bubble, laminar reattachment occurred. The existence of separated flow and flow reattachment causes a change in the effective wing form. Hui and Tamai[71] studied the flow dynamics in the presence of a bioinspired corrugated airfoil. The results showed that the corrugated airfoil outperforms the streamlined airfoil and the flat plate in preventing large-scale flow separation and airfoil stall at low Reynolds numbers. It was discovered that the rising corners of the corrugated airfoil would operate as turbulators, generating unstable vortex formations that would encourage the transition of the separated boundary-layer flow from laminar to turbulent. The unsteady vortex structures trapped in the valleys of the corrugated cross-section would pump high-speed fluid from the outside to near-wall regions, providing enough kinetic energy for the

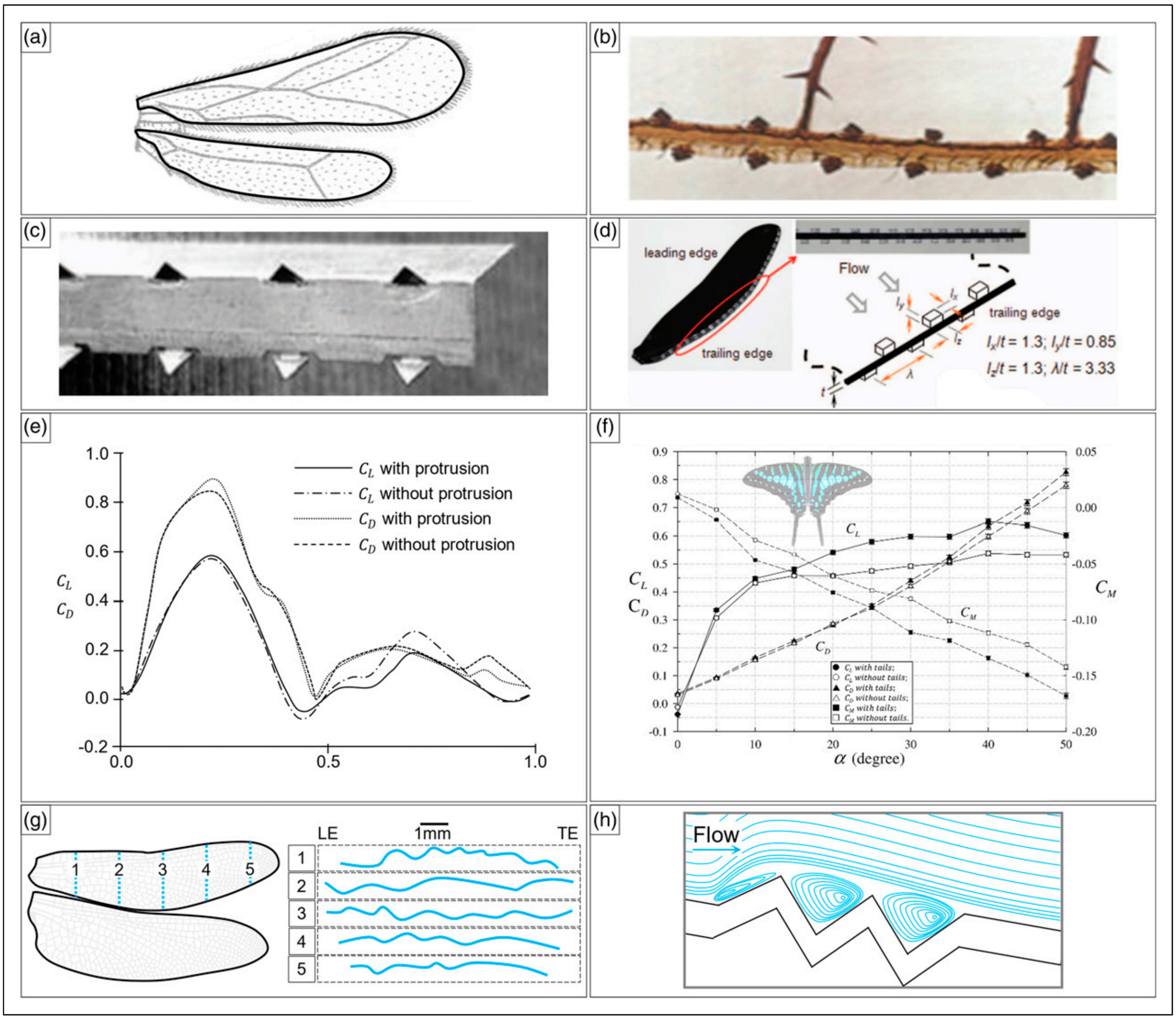

Figure 6. (a) Hairy microstructures at the leading edge; (b) trailing edge of a dragonfly wing magnified view; (c) spade-like protrusion on the trailing edge of an airfoil with a gurney flap; (d) rectangular protrusions on the trailing edge of a dragonfly forewing model; (e) temporal variations of the drag and lift force coefficients on the wing models with and without protrusions[63,67,71]; corrugated surface of dragonfly (Aeshna junca) wing: (f) variation of the lift, drag, and pitching moment coefficients with angle of attack at Re_c = 14400; (g) photograph of cross-sections of forewing of a dragonfly; and (h) streamlines near a corrugated wing at α = 10° in gliding motion.[71,76]

boundary layer to overcome adverse pressure gradients, preventing large-scale flow separations and airfoil stall.

The corrugated design strengthens the wing along its length and decreases stress on the wing membrane. According to research, this sort of wing structure enhances lift force or decreases drag force on a stable wing in gliding flight at a constant angle of attack and Reynolds number in the range of 10^3 to 10^4. The created vortices and separation bubbles are responsible for changing the aerodynamic performance. Separation bubbles in the recesses deliver high-momentum fluid to the wing's upper surface, delaying main separation and boosting lift force. Furthermore, the negative skin friction created by these separation bubbles minimizes overall drag. Also, vortices trapped within the troughs of the corrugations lower local pressure and, as a result, enhance lift force. The vortices formed at the peaks reconnect intermittently to the wing's suction surface, reducing drag force. In general, the varying corrugation geometries alter the interaction between the wing and the vortices and separation bubbles[70–76] (Figure 6(h)).

Conclusion

Insects are one of the most important sources of biological systems' inspiration to control flow and reduce aerodynamic noise, especially while applying passive control techniques. Insects' flight inspiration is challenging due to the wings' flexibility, movement, the difference between the front and rear wings' shapes, and delicacy. The major focus is on flying movement and aerodynamics of wings, according to research papers regarding insect wings. Following that, the focus shifts to insect-inspired flying, wing material, and antibacterial qualities. Additionally, researchers are interested in topics such as wetting ability, sensitivity, and reflectivity.

Bioinspiration from insects might vary based on the need and application. Insects are classified into different kinds, and most can fly by fluttering their wings. In general, insects' flight muscles are divided into direct and indirect types that act synchronously and asynchronously with nerve impulses, respectively. These muscles help insects use a mixture of rotating, flapping, and pitching movements to achieve specific wing kinematics. Insects use various mechanisms for generating aerodynamic forces, including the Weis-Fogh or clap and fling mechanism, delayed stall due to unsteady motion (Wagner effect), wing rotation (Kramer effect), wake capture or wing–wake interaction, added mass, and absence of stall. The insect noises are divided into aerodynamic and structural. Insects' aerodynamic noise is created by fluctuating forces, flow–solid interaction, shed vortex, and turbulence inflow. Meanwhile, insects' structural noise is made by frictional and tymbal mechanisms. Insects' evolution has created some flow control techniques to maximize aerodynamic performance and minimize noise. These techniques can be divided into two major parts: wing shape and sub-structures. Wing shape features such as planform, chord length and location, twist, sweep, wingtip, and AR influence the flow around the insects. The sub-structures such as leading edge, trailing edge, swallowtail, and surface textures affect the flow too.

The influence of the insect wing's sub-structures on controlling flow and noise is full of uncertainties, and we know that uncertainty refers to epistemic circumstances involving incomplete or unknown knowledge. Future research should look at the aerodynamics and aeroacoustics of insects' flapping flight as well as the impact of sub-structures on it. A rectangular plate is a good example of a simple shape to apply the characteristics of an insect's wing to see how they affect flow behavior, aerodynamic forces, and noise generation. These geometric parameters include the camber of the airfoil, radius of the second area moment, twist angle, and AR. A thorough understanding of aerodynamic flight mechanisms, the shape, and the sub-structure of the wings will significantly help engineers to produce competitive products with better aerodynamic performance and aeroacoustic signature. The methods that insects use to control the flow and reduce noise are helpful references for inspiration in making silent wings and blades.

Appendix

Nomenclature

α	Angle of attack
AR	Aspect ratio
b	Wing length
$\bar{c}$	Average chord
MAV	Micro air vehicle
S	One wing area
S'	Two wings area
UAV	Unmanned aerial vehicle

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