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Biophysics of Insect Flight

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Biophysics of Insect Flight

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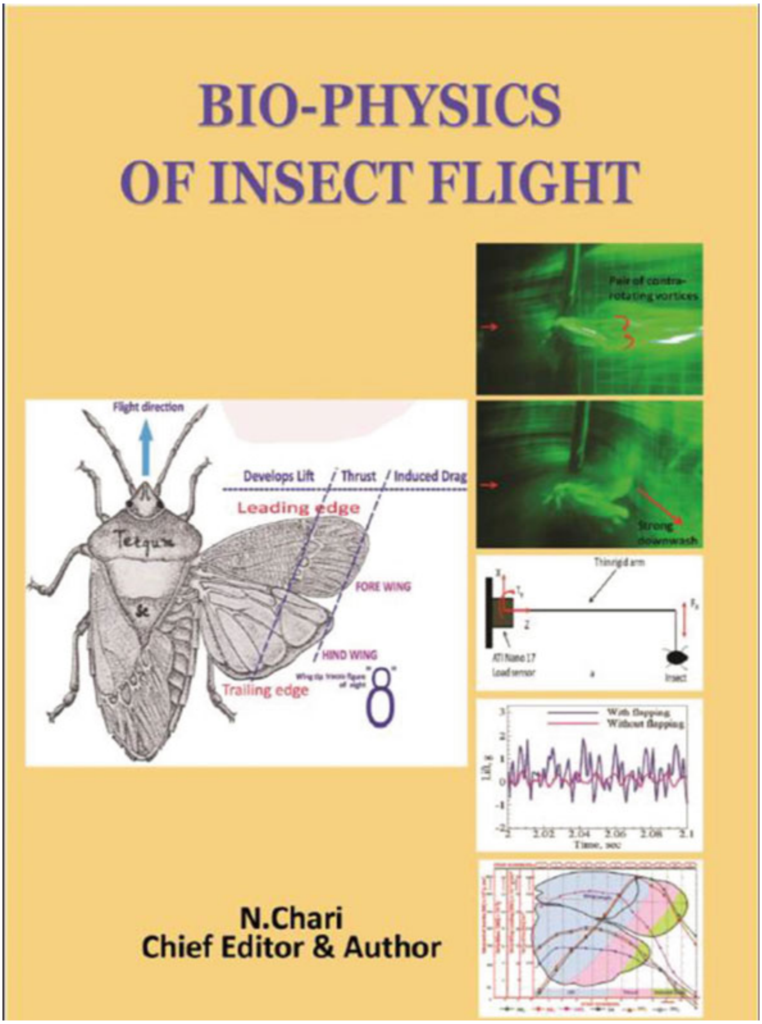

About the Insect in the Figure

Insect flight is characterized by low mass, chitinous flapping flexible membranous wings, low Re, low AR, low L/D ratio, medium frequency and flexible resilin as an elastomer at the wingbase. This book deals with problems associated with MAV prototype design based on the features and characteristics of insect flight.

It may be possible to suggest the design of an experimental/prototype for bio-mimicking insect MAV. The practical problems of nano design come in a big way while dealing with problems of wind flow. Lack of knowledge of flow physics at low Re poses a major hurdle in a thorough understanding of the analysis of insect flight as well as insect mimicking MAV design.

Such MAVs require small flapping flexible wings undergoing structural deformations while producing the required aerodynamic forces. The resulting aeroelastic effects need to be properly understood to get a prototype MAV model. Information on flapping flexible wings is too meager for its design. A possible solution might come by the selective use of nano-technology for the prototype of designs.

Exclusive aspects of insect flight morphology, bio-aerodynamics and Moment of Inertia (MI) have been discussed for developing bio-mimicking prototype Micro Aerial Vehicles (MAV). Major experiments and tests have been carried out on *Tesseratoma javanica* (***T.j***), Soapnut bug as an ideal flier. These insects are found in South Asian countries including India and Africa. A temperature- and humidity-controlled Entodome has been constructed for the first time in India especially for breeding and culturing these wild insects all around the year. The insect flight model could be suggested based on extensive research work carried out for the last fifty years at K. U. Warangal and SNIST, Hyderabad.

A nano-torsion balance was used at National Aerospace Laboratories (NAL) to measure various aerodynamic forces like thrust, lift and body mass, which is of the order of less than a gram. Wings on both the sides weigh about 20 mg. The lift and torque forces in the tethered flight of ***T.j*** are observed on an oscilloscope for measuring the bioacoustic sound and aerodynamic forces. Thoracic pro-scutellum shape and tergum (geometry) play a vital role in this insect flight. Soapnutbug is a moderate high-frequency flier.

The smoke studies are conducted on a live insect to study the flow visualization with and without flapping for the first time by collaborating with the scientists from NAL-MAV unit, Bangalore. Further detailed experimental studies are under progress. The wingbeat frequency, lift and torque parameters have been estimated in tethered flight by using a sensitive torsion balance. A low-speed wind tunnel was fabricated for estimating frequency, velocity and other aerodynamic forces.

The MI characteristics and Wing Loading studies have been carried out extensively on *T.j* by using the strip-analysis method. These studies are helpful to estimate wing geometry, wingbeat frequency, associated aerodynamic parameters and wing designs. Wingspan loading studies have been suggested for understanding insect flight since this parameter happens to be the ratio of wing loading to aspect ratio and is of practical importance in comparative bio-aerodynamic studies, leading to nano-technological bio-mimicking designs.

Preface

I am highly obliged to **NDRF** authorities, Bangalore, for financial assistance, encouragement and kind cooperation. The author is grateful to **Honourable Secretary**, **Dr. K. T. Mahhe** and **Executive Director**, **Prof. P. Narasimha Reddy, SNIST** for the generous facilities, encouragement and support for completing this project. I appreciate all my co-authors for their kind cooperation, patience and encouragement during difficult times.

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Hyderabad, India

N. Chari
Chief Editor and Author

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Chapter 1
Introduction

N. Chari and Ponna Srinivas

Abstract A brief account of morphological and anatomical features of an ideal flying insect has been mentioned. Flight apparatus of insects, in its structure basically differs from that of Homeotherm fliers, such as those of birds and bats. Structurally they are analogous type. Postembryonic development involves metamorphosis as in housefly and silkworm which is regulated by endocrinegland secretions. Morpho-functional–anatomical features of insect flight study helps in designing micro aerial vehicles (MAV).

Keywords Morphology · Anatomy · Chitinous wings · Flight apparatus · Resilin · Metamorphosis · Biomimicking aerial vehicles

Introduction

Entomology is the branch of Zoology that deals with the study of insects (Entomon—insect and Logos—discourse). Insects are the most successful class of fliers in the animal kingdom and they constitute nearly seventy-five per cent of the recorded fauna with their ability to fly. Insect flight is a technical marvel of nature, developed during the course of the prolonged period of evolution. These are miniature flyers. Flying for nearly three hundred million years successfully and feeding on plants such as *Pteridophytes* and *Gymnosperms* and *Angiosperms* in a warm and humid climate. Insect flight apparatus has evolved ***denovo*** as compared to other 'natural fliers' phylogenetically and structurally. Insects are the only invertebrates that have the flying capacity in the animal kingdom. An understanding of insect aerodynamics requires an inter-disciplinary approach involving bio-physical, mathematical, aeronautical and nanotechnological approaches. They are the most diverse fliers in contrast to birds and bats. Insect bio-diversity accounts for their successful adaptation to various ecological niches and their survival and migratory capability. As

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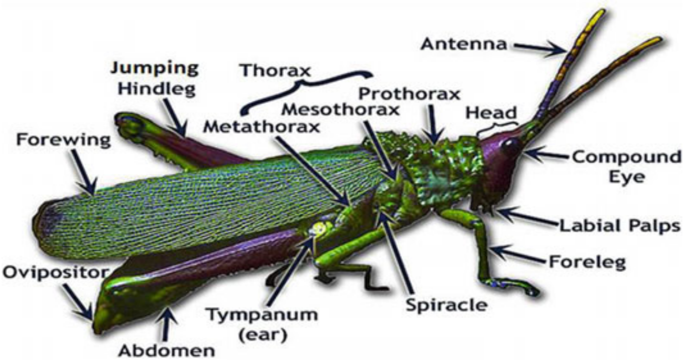

Figure. 1.1 Morphology of a typical insect (Adapted from various sources)

such, the mechanism of insect flight is not fully understood even to this day. The wing movement is quite prominently of flapping type and highly complex. The ability to fly has played a major role in their worldwide distribution, biological survival, migration and navigation of these fliers. Numerically insects form nearly three-quarters of a million (750,000) living species and form a major essential link in the life chain of biological systems [1]. A deep understanding of insect flight offers a very good example of morpho-functional correlation needed for understanding the biomechanical design of MAVs as well as the associated features of the flapping flexible wings. Insects are distributed all over the world. The evolution of insect flight as a marvel of nature remains to be elucidated fully Fig. 1.1.

General Characters

Morphological Features

(1) Flying insects have a streamlined body with a distinct head, thorax and abdomen, and for improved flight capability, a pair of wings offering less drag.
(2) The head has mouth and associated mouthparts, compound eyes and a single pair of sensory antennae. The mouthparts usually are of biting, chewing, sucking and piercing type. The head is formed due to the fusion of six segments during development.
(3) Each compound eye that gives a mosaic image has many functional single units known as ommatidia. The number of ommatidia varies in different fliers. The dragonfly has 10,000 ommatidia.
(4) Ocelli are small simple eyes having a lens and a retina found on the top of the head between larger compound eyes. Compound eyes can sense 'optic flow'

and recognize targets. 'Optic flow' is the apparent movement of texture in the visual field during flight. Some principles of visual guidance (optical flow) may be shared by diurnal fliers, as reported in honey bees and bumblebees as they use optical flow cues during their flight.

(5) Antennae help in directing motion, body orientation and detection of odour, sound, temperature and humidity. All insects possess a pair of antennae that help in flight stabilization and primarily act as sense organs and bear sensillae.

(6) Thorax has three segments, pro, meso and metathorax. It is the main structure for flight and locomotion (walking). Thorax is the main locomotor centre of the body in insects as compared to other arthropods. Tergum plays a major role in flight, by directing airflow.

(7) A pair of the membranous wing is present on meso and metathorax laterally. These two segments are together known as pterothorax. Many insects have two pairs of wings on pterothorax, which are held together by suitable coupling devices during flight. The housefly has one pair of functional wings on pterothorax which is common in Diptera.

(8) Insects are hexapods, having jointed legs for walking, swimming and jumping into the air and a pair of chitinous membranous wings for flight on pterothorax.

(9) Each leg contains six jointed segments. Three pairs of legs are present on the ventrolateral sides of the thorax. One pair of legs is present on each thoracic segment.

(10) The abdomen has no legs. The terminal part of the abdomen helps in excretion, sensory and reproductive functions. The abdomen has relatively simplified segmentation. The abdomen normally has ten segments; however, their number is variable in different orders and the last segments are modified as genitalia.

(11) Light- and sound-producing organs are also present in some insects such as beetles, cicada and some plant bugs. Lampyridae (Coleoptera) is the best-known luminescent group. Usually, the females are sedentary and attract the males. The tymbals of Pentatomidae get buckled and produce sound. Cicadas represent the highest development of sound production in insects. The ears are also found in a great variety of insects.

Reaction involving light production is given below:

Mg++, Luciferase (Enzyme)
Luciferin + ATP --------------------------------------> light production

Wings

(1) Body covering and the wings are made up of chitinous exoskeleton which is chemically a polymer of *N-acetyl glucosamine*. The integument gets hardened

into an exoskeleton of chitin. The chitinous exoskeleton also serves as a protective cover, helps in attachment to muscles and acts as a water-tight barrier and a sensory surface by developing sensory hairs (sensillae).

(2) During the early stages of evolution, wings were useful for short-distance passive flight, parachuting and gliding followed by flapping flight including rotation of the wings. Flapping flight helps in the production of aerodynamic forces such as lift, drag and thrust. Figure eight flapping contributes to lift and thrust forces.

(3) Some non-flying insects known as *Apterygota* and some others are fully flying and known as *Pterygota.* Apterygota are primitive insects and the pterygota are more advanced.

Respiration

(1) The flying insects have adapted for aerial life and breathe by spiracles and the tracheal system as in some other arthropoda such as scorpions, spiders and centipedes.

(2) The insect respiratory system includes paired segmental openings known as spiracles and branched tracheal systems. Separate opening and closing mechanisms are present for the spiracles in the thorax and abdomen having separate structures.

(3) There are nine pairs of spiracles of which two pairs are found in the thorax and seven pairs in the abdomen which differ structurally.

(4) External air flows into the body through spiracles (stomata) and the branched tracheal system supplies oxygen to different organs and cells. The tracheal system has contributed to the evolution of insect flight in terms of O_2 supply and high oxidative metabolism.

(5) Spiracles help not only in respiration, but also prevent evaporation of moisture, entry of dust and small foreign particles into the respiratory system. Spiracle-like structures are also present in some other arthropoda such as spiders, centipedes and millipedes.

(6) Air sacs are dilations of the trachea and are abundant in flying insects such as grasshoppers, flies and bees.

(7) Tracheal gills are present in some aquatic insect larvae such as larvae of Odonata. Culex larvae have paired lateral branches leading to enter the respiratory siphons. Aquatic insects also breathe by ‘Plastron respiration’. Dytiscidae and Bellastomidae breathe by plastron respiration.

Flight Apparatus

(1) Membranous wings have elastic hinge-like joints containing axillary sclerites located at the wing base. There is also resilin (elastomere) at the fulcrum and

these function as a perfect mechanical spring. During flapping, movements occur either at low, medium or high frequencies. It may be noted that insects cannot fly if the resilin gets damaged or dissected. The resilin helps in wing folding at rest.

(2) A large number of longitudinal veins are present within the wing which strengthen the wing membrane. The venation pattern of wings differs from order to order in insects. Venation also plays an important role in insect classification and identification at various levels. Aeroelastic effects in moving flexible wings are mainly responsible for developing structural deformations and aerodynamic forces which contribute to the flight.

(3) Wing venation and resilin influence the aeroelasticity of the wings significantly during flight by way of axial stretching, buckling and resulting damped vibrations. This needs further study.

(4) The wing membrane is formed by two thin layers of integument which are sandwiched and enclose the trachea, nerve, haemolymph and veins.

(5) Resilin present at the wing base is four times more elastic than natural rubber. It stores up to 80% of potential energy during its wingbeat. It is an important protein-based elastomeric biomaterial. Resilin has 100 times higher storage capacity for elastic energy than muscle. It does not undergo fatigue as compared to muscles.

(6) The direct and indirect muscles of the thorax play a major role in insect flight. The indirect muscles, i.e., Dorso-Longitudinal Muscle (DLM), span the tergum. Dorso-Ventral Muscles (DVM) extend from tergum to sternum. The direct muscles are attached to pleuron and sclerites at the wing base.

(7) Direct flight muscles are attached to the wing base of *mayflies* and *dragonflies* which are primitive insects. Indirect flight muscles are generally well developed in advanced insects like honey bee, housefly and plant bugs, and they are attached to the thorax.

(8) In mayflies and dragonflies, a small downward movement of the wing base lifts the wings themselves upward. Indirect flight muscles are attached to the thorax. The deformation of the thoracic tergum leads to the movement of the wings. This partly explains the role of direct and indirect flight muscles during flight.

(9) There are also accessory indirect flight muscles that help in modifying wing movements including wing rotation.

(10) The linear or rotatory wing movements of flapping flexible wings are quite complex. Approximately, a figure of '8' is traced at the wingtips, which can be observed through a stroboscope in Cicada, soapnut bugs and house flies.

(11) Generally, large insects like dragonflies, cockroaches, grasshoppers, butterflies and moths have larger wings exhibiting a low wingbeat frequency. Smaller insects like mosquito, housefly, drosophila, etc. flap their wings at high wingbeat frequency (250–1000 Hz). During hovering, wingtips trace a figure of '8'.

(12) Apart from having low wingbeat frequency (30–40 Hz), insects like dragonfly and mayfly possess complex mesh type of wing venation and cannot fold their wings as in other insects.

(13) Variations are found in the wing structure of several orders. Beetles (Coleoptera) possess two pairs of wings, of which the first pair is hard and leathery known as elytra. This is partially true for some *Heteroptera*. In housefly (Diptera), the second pair of wings become rudimentary, acting as halters to balance during flight and vibrate for detecting changes in direction. They are gyroscopic in their action. Halters vibrate out of phase with the wings and they can detect very fast rotation.

(14) Bumblebee, honey bee and wasp (*Hymenoptera*) have two pairs of thin membranous wings, while thrips have small fringed wings.

(15) Plant bugs (*Heteroptera*) have the first pair of partially chitinous wings and the second pair of thin membranous wings. In *Homoptera,* both the wings are similar as in cicada which make figure of '8' (as in Hummingbirds).

(16) Mostly, the first and second pair of wings on each side of the thorax get coupled by special hooks and move as a single unit during flight.

(17) By moving the wings up and down, insects take advantage of unsteady mechanisms (delayed stall, rotational lift and wake capture) for their flight.

(18) The evolution of insects and their successful flight was the result of their low body mass, membranous wings, elastic resilin at the fulcrum, as well as coupled with a relatively high wingbeat frequency, spiracles and tracheal system supplying more oxygen to oxidative aerobic flight muscles, open circulatory system and chitin as the exoskeleton.

(19) Robotic insect fliers using Micro-Electromechanical Systems (MEMS) designing for bio-mimicking MAVs have been suggested. However, it is rather difficult to use in the design of bio-mimicking MAVs.

Anatomy

(1) Insects have evolved successful flight due to a systematic arrangement of several systems (digestive, circulatory, excretory and reproductive) which are medially located in the body. The dorsal location of pulsating tubular heart is a notable feature. There is no haemoglobin in the blood. The heart is typically divided into chambers varying from 1–9. The circulatory system is open. The ventral solid double segmental ganglionated nerve cord has been derived from Annelid ancestry.

(2) The blood or haemolymph consists of fluid plasma having nucleated cells and no haemoglobin.

(3) Some of the bio-mimicking flight characters in biological flight as mentioned are common to insects, Micro Air Vehicles (MAVs) and Nano Air Vehicles (NAVs). Hence, the study of the Aerodynamics of Insect Flight is essential for a better understanding of the various parameters required in the design and

development of MAVs with flapping wings. Hence, the understanding of flight anatomy is rather essential.

(4) Excretion is by malpighian tubules. They help in osmoregulation and excretion and pour their secretions in the midgut (hindgut). Adipose tissue or fat body is well developed in insects since it supplies large amounts of energy for flight. Sexes are usually separate. Usually, the external genital aperture of a female insect is found in the eighth abdominal segment and that of a male in the ninth segment. Always fertilization is internal. Parthenogenesis and viviparity are also known.

(5) Development involves complete metamorphosis having egg-larva-pupa and adult as in housefly and butterfly. Endocrinal glands play a vital role in postembryonic development. The moulting hormone or ecdysones secreted by prothoracic glands and juvenile hormone by corpora allata are responsible for the metamorphic changes.

(6) Life History: Cockroach has an egg case known as ootheca. It has 16 fertilized eggs inside. The cockroach is paurometabolous. The development is gradual through the nymphal stages (five). The nymph resembles the adult except in size, colour, sexual maturity and lack of wings. The life history of termites is extremely complicated. For complete metamorphosis, the silkworm is a good example.

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Chapter 2
Flight a Retrospect a Brief Review

N. Chari and Ponna Srinivas

Abstract This review of literature on Biophysics of Insect Flight can broadly be divided into four subdivisions. Early experimental investigations on wingbeat frequency and related parameters using simple mechanical, optical and electrical devices were carried out during 1934–1955. Advanced flight techniques for finding wingbeat frequency, wing mutilations, vortex theory, wing kinematics and detailed lift enhancing mechanisms were developed during 1956–1984. During the period of 1985–2008, studies on power requirements of a few insects have been analyzed. Shyy et al. (Prog Aerosp Sci 46(7):284–327, 2010) have discussed progress in the aerodynamics and aeroelasticity at low *Re.* As *Re* increases, velocity also increases. Recently, researchers are exploring the possibility of designing the Biomimicking MAVs based on the principles of insect flight. We may be able to design the MAV of Insect size in a decade or so.

Keywords Lift enhancing devices · LEV · Wing kinematics · Low *Re* fliers · Vortex textures

Review of Literature

Early experimental investigations of insect flight were carried out by Magnan [1]. He used a high-speed photography technique to study the pattern of wingbeats and also to determine wingbeat frequency. Chadwick [2] used the electronic stroboscope for determining the wingbeat frequency of insects in tethered flight. Pringle [3] described the gyroscopic mechanism of *halters* in Dipteran fliers. He also explained "Excitation–Contraction-Coupling" of insect flight muscles. Pringle also reported that fundamental thoracic movements in insects are identical with the wingbeat frequency. He used piezoelectric crystal, phonograph pick up and an oscilloscope to study the wingbeat frequency of insects.

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Osborne [4] interpreted Magnan's Data for giving elaborate mathematical treatment for understanding the flight characteristics. He assumed that the force developed by the wingbeat is proportional to the square of the velocity of the forward flight. He also derived a general equation for the lift and drag coefficients (C_L and C_D). Roeder [5] studied the thoracic movements and electro-potential variations in flight muscles of insects during flight. He also used the piezoelectric phonograph method for studying the wingbeat frequency. Sotavalta [6] reported the essential factors regulating the wingbeat frequency of insects due to wing mutilation and loading. Chadwick [7] reviewed the motion of insect wings. He reported an increase in wingbeat frequency with age and temperature in Drosophila. Sotavalta [8, 9] has analysed the wing stroke frequency and conducted mutilation studies and suggested the terms such as Neurogenic (Synchronous) and Myogenic (Asynchronous) fliers. There is also a difference in the structure and physiology of these muscles including tracheal supply and metabolic pathways.

Weis-Fogh and Jensen [10] elucidated the basic principles of insect flight on the basis of biology and physics of flight of desert locust, *Schistocerca gregaria*. They analysed wing kinematics using polar curves and calculated lift and drag coefficients (C_L and C_D). This is one insect where the morpho-functional relation of flight apparatus and aerodynamics has been relatively well understood. Weis-Fogh and Jensen [10] further explained the aerodynamics by using the blade element analysis. He concluded that for a tethered desert locust, the downstroke of the wings was responsible for both lift and thrust production. The upstroke is more or less a recovery stroke and does not require much metabolic energy. Pringle [3] in his book on Insect Flight reviewed the basic anatomy and physiology of pterothorax of various insect fliers. Greenwalt [11] opined that the wings of birds and insects may be assumed as mechanical oscillators and developed a differential equation for computing the wingbeat frequency in hovering. Greenwalt subsequently based his study on wing length and expressed millimetre as a basic unit in his calculations. However, the derived equation for calculating hovering frequency is quite complex. Sotavalta [12] has analysed the flight acoustics and wingbeat frequency of Bombus, a *Hymenoptera*. Anderson and Weis-Fogh [13] have described resilin elastomere protein which is found well developed at the base of the wings and is responsible for the feasibility of high-frequency flight in insects. Recently, molecular cloning techniques have been used for constructing resilin-based proteins. A number of formulae as suggested by various authors for the calculation of wingbeat frequency based on flight parameters have been discussed by Chari [14]. In hovering flight weight of the flier is equal to lift and lift is proportional to hovering frequency.

Bennett [15] studied the wing of *Melolantha* as a model for the study of flight kinematics. He emphasized the significance of unsteady flow over the airfoil of a flying insect. Vogel [16] has showed that inertia of the boundary layer could be a significant factor for the mechanics of Resonant-Wing-Thorax System of insects. He also studied the flight kinematics of Drosophila by using a photographic technique. Pennycuick [17] has explained hovering flight by using a helicopter model. Crawford [18] proposed a relation for the wingbeat frequency of small flier in hovering based on Newton's laws. He presented a theoretical relation for wingbeat frequency depending on wing swept area, small mass of the flier and density of the air. Crawford's formula holds good for small insects like mosquitoes. Weis-Fogh [19] discussed the hovering flight in nature by applying the actuator disc concept and momentum jet theory for insects having the Reynolds number ranging from 10^2 to 10^4. Weis-Fogh [20] studied flapping velocity as a simple harmonic motion for a semi-elliptical wing. Lighthill [21] found that the wasp *Encarsia* was using a horizontal stroke plane and circulatory lift mechanism during hovering.

Bennett [22] proposed a differential velocity model, that is, the downstroke velocity during a wingbeat is found to be significantly greater than the upstroke, which is notable since the downstroke is a powerful stroke and the upstroke is a recovery stroke. Puranik et al. [23] used classical methods for measuring wingbeat frequency in the tethered flight of soapnut bugs (*Tessaratoma Javanica*), by using a *hydrophil* balance and adopting Melde's experiment. Natchtigall [24] described the wing movements of Formia. Norberg [25] recorded the wingbeat movements of a dragonfly during normal flight. Rainey [26] showed that the elasticity of flight muscles is an important factor and needs to be considered in insect flight studies. Norberg [27] used a modified force balance to measure mean lift and drag coefficients. Pringle [28] has observed that aerodynamic forces are generated during wing movements. The high wingbeat frequency of insects is attributed to the mechanical resonance of the Wing-Thorax-System. The wing-thorax system in Diptera appears resonant which may contribute to propulsion. Ahmed [29, 30] conducted the Fourier analysis of flight sound of a soapnut bug. They have used a bio-acoustic technique. Weis-Fogh and Alexander [31] have calculated the mechanical power output of muscle irrespective of size. Aravind Babu et al. [32] reported the aerodynamic parameters of a pentatomid bug in detail. Chari et al. [33] reviewed the flight adaptations of insects, birds and bats. Ellington [34] proposed the vortex theory of hovering based on blade element models. Baker et al. [35] described wingbeat frequency, flight speed and altitude in free flight for *L.Migratoria*. Vogel [16] has calculated the drag coefficient for Drosophila.

Ellington [36–38] gave a detailed description of morphological parameters related to flight. Casey et al. [39] elucidated the flight energetics of bees in relation to their morphology and wingbeat frequency. Broadskii [40, 41] has discussed vortex formation in the tethered flight of the butterfly and the evolution of insect flight.

Puranik and Chari [42] have explained the theoretical basis for calculating the frequency of wingbeat depending on aerodynamic parameters based on body and wing morphology. Recently, lift-enhancing devices have been reported by various authors.

a. Clap and Fling Mechanism
b. Rapid Pitching up Rotation
c. Wake Capture
d. Delayed stall of LEV
e. Tip Vortex and
f. Passive mechanisms.

The detailed study of these mechanisms might help in the design of improved wings for bio-mimicking MAVs operating at low Reynolds number.

Ravi [43] in his thesis has studied the aerodynamic parameters and power requirements of a pentatomid bug in detail. Vydehi [44] has elucidated the unique flight features of a soapnut bug. Vydehi in her thesis and subsequent publications included the basic and derived parameters and their significance in the study of insect flight. Dickinson et al. [45] explained three main principles to explain insect flight effectively viz.,

a. Specific kinematics of wing motion during flapping and rotation
b. Ability to delay flow separation from the wing
c. Using the energy of vortex wake.

Significant factors in the study of the aerodynamics of insect flight have been reviewed by Sane [46]. This inspires in developing bio-inspired MAVs and flapping wings as prototypes. Shyy et al. [47] discussed elaborately and summarized recent progress in flapping wing aerodynamics and aeroelasticity at low *Re*. MAVs have the potential to revolutionize sensing and information gathering, such as environmental monitoring and homeland security as and when required. They also considered the role of spanwise flexibility in the forward flight which influences shape deformation and also the effective change of angle of attack along the wingspan.

Insect flight due to flapping of wings mostly depends on structural deformations influenced by aeroelastic properties. This knowledge in turn could help in a better understanding and possible design of flapping flexible wings.

The present review covers "the basic principles underlying flapping flight in insects, results of recent experiments concerning the aerodynamics of insect flight, as well as the different approaches used to model these phenomena".

Recent Findings

The concluding remarks of Shyy et al. [47] based on Aerodynamics of Low *Re* fliers can be summarized as follows:

1. They have discussed various low *Re* fliers, flight characteristics and scaling laws related to wingspan, wing area, wing loading and body parameters.
2. The lift to drag ratio of a flier decreases as *Re* drops 10^4. A corrugated dragonfly wing exhibiting anisotropic properties can develop favourable lift as compared to a non-corrugated wing surface because of viscous effects. Wind gusts play an important role in low *Re* fliers having low mass. The tip vortex induces a downwash effect for a low Aspect Ratio (AR) and low *Re* fliers. The wingtip vortices reduce the lift force.
3. For the design of flapping wing MAVs, an understanding of kinematics, vortex structures and Reynolds number are essential. When we think of MAV design based on insect flight, the considerations of moderate frequency, multi-scale

problems, unsteady aerodynamics, wind gusts and vehicle control problems have to be considered seriously.

Mukharjee and Omkar [48] stated that lift generation mechanisms have been identified first experimentally and then confirmed by numerical simulations. An understanding of the complete aeroelastic behaviour of wings is essential in order to appreciate their aerodynamic performance. Shyy et al. [47] studied drag characteristics of three aerofoils with different flexibilities in a sinusoidal oscillating free stream. They concluded that modulating the flexibility can improve the aeroelastic characteristics and thrust. The translational phase of wing rotation consists of phase reversal in flapping cycles known as pronation and supination. The sweeping motion of the wings coupled with pure pitching occurs during the rotary cum flapping motion of the wings.

Flexible wing structures of simplified insect-sized flapping MAVs have been elucidated based on the 1-DOF butterfly model, others on the 2-DOF Diptera model [49]. French researchers, Vanneste et al. [50] conceived a design of Flapping Wing for Nano Air Vehicle (FWNAV). It is basically a scaled-down version of the flapping wing with a wingspan below 7.5 cm. Lift generation involves a more complex fluid–structure interaction in FWNAVs. Wing roots can be actuated on various degrees of freedom. The authors conceived a method for wing optimization by playing with mesh size and the number of time steps in the mean lift computation.

Ho et al. [51] discussed in detail unsteady aerodynamics and flow control and use of MEMS as applicable to flapping wings of MAVs. Sibilski et al. [52] indicated that a good model of MAV needs rotation of the wings in addition to flapping during downstroke and upstroke for producing sustained aerodynamic forces.

Curet et al. [53] studied the wings for MAVs and suggested that when a thin wing is stationary, it spontaneously flaps at a critical wind speed. Lift is enhanced and it also increases drag. Enhanced lift is mainly due to strong Leading Edge Vortices (LEVs).

In the case of insects and other avian fliers, however, the evolution from parachuting to gliding to the powered flapping occurred due to the compliant wings with positive camber and necessary structural deformations for the development of required aerodynamic forces. A suitable note may be taken of these features for the design of practical Insect Bio-mimicking vehicles.

Summary

This chapter gives a brief review of the general introduction to insect biological features, morphological characteristics, wings, respiration, various anatomical and flight considerations to establish a base for the engineers to understand differential aspects involved in the design of a bio-mimicking MAV based on the above insect features.

Thereview of literature can broadly be divided into four subdivisions:

1. 1934–1955: Covering early experimental investigations.
2. 1956–1984: Covering flight techniques, morpho-functional correlations, review of wingbeat frequency, vortex theory and wing kinematics have been considered and a brief account of lift-enhancing mechanisms has been outlined.
3. 1985–2008: Aerodynamic parameters and power requirements of a few insects have been discussed. Sane [54] reviewed the detailed study of the aerodynamics of flight. Shyy et al. [55] discussed progress in aerodynamics and aeroelasticity at low *Re*.
4. Recently, many authors have considered simplified insect-sized models for the design of MAVs. Very recently, some interesting suggestions have been made by Ho et al. [51], Sibilski et al. [52] and Curet et al. [53]. This review clearly shows that within the next few decades, we may be able to design Insect Bio-mimicking MAVs.

Though this chapter is limited to the bio-aerodynamic aspects, it gives relatively a brief and clear idea for an engineer to follow and understand the relative importance and role of each physical and biological descriptive (qualitative) aspect which gives inspiration for the design of bio-mimicking vehicles.

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Chapter 3
Aerodynamic Considerations

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Abstract The different aspects of insect flight and aerodynamics covered in this chapter can briefly be summarized as below. Insects are the first class of invertebrates which differ phylogenetically, morphologically and structurally from vertebrate fliers. Wings of birds, bats and insects are structurally analogous and the aerodynamic forces developed by them are in a homologous fashion. Insect fly at low Re ranging from 1 to 10,000, where viscous and boundary layer separations are predominant. Various lift generating mechanisms include Wake capture, Passive pitch, Tip vortex formation, Rapid pitching rotation, Clap and fling mechanism and LEV helping in delayed stall. The stalling angle (AOA) for an aeroplane is limited to 16–20°. However, for a flying insect, prestall period extends from 45 to 75° and stall may occur at 90°. Sensory feedback is very well developed in the insects. In Neurogenic fliers the frequency is variable from 2–100 and in myogenic it varies from 100 to 1000. Elastomere resilin is well developed and plays a key role in insect flight. The actuatordisc concept helps in calculating hovering frequency even in Biomimicking MAVs.

Keywords Lift devices · Lift and drag coefficients · LEV and delayed stall · Actuator disc · AOA · Circulatory flowα

Introduction

Aerodynamics is a branch of science of Fluid Mechanics and Aeronautics which relates to all activities pertaining to aerial locomotion. Aerodynamics, in simple words, is defined as *"the science which deals with the study of motion of air around*

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the flier and subsequent motion of the body through air" [1]. It also deals with the analysis of various forces generated as a result of the motion of objects through air and the mechanism or 'the art' of sustaining a flier, quite often heavier-than-air, flying object, or a machine afloat and making it move forward. These aerodynamic forces are influenced to a great extent by the aero-thermodynamic conditions of the air viz., the ambient pressure and temperature which control the density of the surrounding air, flight Mach number and the presence of aerosol. In this context, the geodetic location or the altitude of the flying object above the ground or water surface plays a key role. The viscous nature of air also affects the flight of the object depending on whether the velocity of the flier results in laminar, transition or turbulent boundary layers on the critical surfaces controlling the flight. The flight is also affected by the Reynolds number which can be defined as the ratio of inertial forces to viscous forces. This may be the case for all flying objects. Likewise, the Mach Number (M), a ratio of flight velocity to the local speed of sound, affects high-speed flight. If M is less than 0.3, the flight is in an incompressible regime as is mostly the case with Micro Aerial Vehicles (MAVs) and the biological fliers. This is not generally true for an aircraft due to its larger speed and high altitude flight. The biological flier or the aircraft in these cases is supported by its wings and literally floats in the air. This is true for the insects with low mass as well. The different forces predominant in this kind of flight are aerodynamic forces comprising of vertical lift, forward thrust and drag in addition to the weight due to the downward gravitational pull on the flier. The lift forces help in overcoming the downward gravitational pull and help the flier to take off from the ground or rise to different heights. Similarly, thrust is needed for the flier to propel forward and to provide any necessary forward acceleration for increasing the speed (velocity) of flight. It may be noted that the greater the forward velocity, the greater is the thrust needed to overcome the aerodynamic drag and other resisting forces.

The biological fliers comprising of birds, bats and insects have differences in phylogeny, structure and physiology. However, these fliers are many times superior to man-made flying objects like the aeroplanes and helicopters, during their low-speed flight. The rockets and missiles operate at much higher speeds. The aeroplanes, for example, derive their forward thrust through the propellers or the propelling jet, and the lift is generated by the relative airflow over the asymmetrical or cambered, fixed-wing surfaces, which are suitably contoured. The helicopter rotor by virtue of the blade pitch angle settings is both collective and cyclic and the blade rotation develops the necessary lift as well as the forward thrust. A tail rotor helps in producing the balancing counter-torque to arrest the body rotation. The alteration in the lift force in a fixed-wing aircraft is achieved by adjusting the angle of attack which controls the relative direction of airflow with reference to the wing chord-line. The greater the angle of attack, the higher is the lift developed. In the case of fixed-wing aircrafts, if the angle of attack exceeds around 16°, it is counterproductive with the resulting stalling and separation of the airflow over the wing. This leads to a total loss in the lift, increased drag and a possible loss in height of the flier leading to an accident. It may be mentioned that it is usually very difficult for the aircraft to recover from the stall and restore its normal flight. It is interesting to note that in many biological fliers including insects, the wings can tolerate much higher angles of attack before stall, implying higher stall margins. The cyclical motion of the flapping flexible wings and fast feedback sensory systems delay the insect stall considerably through larger angles of attack and help them to recover from eventual stalling by prolonging the pre-stall period considerably as compared to an aircraft stall.

The biological fliers are quite different from the man-made aeroplanes, missiles or helicopters. They exhibit the salient features of *flapping wings* in their flight. This is nothing but the simultaneous moving of the wings in oscillating or flapping mode along with a twisting motion of the wing. The extent of flapping with an added twist is decided by the flier in-situ depending on the wing structure and the instantaneous flight requirements. They have different modes of flight viz., Flapping, Hovering, Bouncing, Gliding, Thermal Soaring as well as Passive flight. It may be mentioned here that many insects have two sets of wings, with one pair partly overlapping the other pair. However, in dragonflies, the individual wings can move independently. The housefly, for example, possesses one pair of functional wings that develop all the required aerodynamic forces. Another interesting feature existing in some insects is the *clap* and *fling mechanism* during the flight which also enhances the lift. There are six additional lift-developing mechanisms.

Certain asymmetry can be noticed in the downward and upward stroke or 'beats' of the wings. The downward stroke is a high-powered stroke that produces sufficient lift forces for the insect to gain height or sustain its altitude position during hovering. The upward stroke, on the other hand, is of relatively lighter intensity and is a *recovery stroke*. The period of downward stroke is generally more than that of upward stroke. In the case of ***T.j***, downward and upward stroke periods are 14 and 6 ms and the total stroke period is 20 ms. The downward and upward strokes put together constitute one wingbeat cycle. The number of such beats or cycles per second is termed as the wingbeat frequency and is expressed in cycles per second (cps) or Hertz (Hz). In insects, the wingbeat frequency varies from 2 to 1000 cps. Based on the rate of the number of wingbeats, they are grouped as *Neuroegenic fliers* (2–100 cps) and *Myogenic fliers* (100–1000 cps), depending on neuronal impulses and subsequent muscle oscillations (Tetanic). Myogenic muscles are more oxidative as compared to neurogenic muscles.

One further characteristic feature of the biological fliers is the way they simultaneously generate the necessary lift and thrust by the typical stroke pattern of the flapping flexible wings. The wings not only make an up and down oscillatory motion, but they also make a partly twisting motion of the wings originating from the wing base. In this process, a typical shape of **'8'** is generated by the wing tip which can be observed through a stroboscope by virtual freezing of the wing images. There is a large variation in the size of the fliers and their wings as well as the body mass which may extend from a few milligrams as in small insects up to a few grams (60 gm) as in larger *beetles*.

Modes of Insect Flight

Insect flight is complicated as compared to other biological fliers due to their small mass, presence of elastic resilin at the wing joints and varieties of flexible flapping wings adapted for high-frequency flight. These types of flight can broadly be classified as follows:

(i) Hovering Flight
(ii) Forward Flight
(iii) Gliding Flight
(iv) Manoeuvring Flight
(v) Passive Flight.

(i) **Hovering Flight**: In hovering flight, forward velocity is nearly zero and the flier remains in equilibrium more or less in a stationary condition. The insect wing generates the necessary lift mainly during the downstroke and to some extent during the upstroke. The hovering position is usefully adapted for feeding such as nectar sucking from flowers and in some cases blood sucking from its prey. The hovering also helps in the surveillance. The wing span remains more or less constant and the wingbeat is continuous. During hovering, the body axis is slightly inclined with the face upward and the wing tip movements describe a figure of '8'. Hovering is a costly mode of flight in terms of energy consumption. During hovering, the intake of oxygen as well as the energy consumption increases by more than five times as compared to the resting metabolic state. It may be noted that the hovering process results in the creation of a set of standing vortices one above the other. This is in contrast to the forward flight. Honey bees and Bumblebees are good examples of hovering insects during nectar sucking. Hence, the insects must draw cleaner and fresher air from the ambient flow and get rid of the vortices they have created to obtain a periodic lift [2]. Basic aerodynamic mechanisms in hovering insects might help in the development of insect-inspired Bio-mimicking MAVs [3–5]. The swimming motion during hovering produces a figure of '8' by the wing tips which is an efficient one.

(ii) **Forward Flight**: Insect flight is mainly due to a powerful downstroke and an upward recovery stroke achieved through powerful muscular movements. Forward flight of insects comprises of upward lift and forward thrust against gravitational force and drag. Insects have less body mass and relatively larger wing area per unit mass as compared to Homeotherm fliers (i.e. birds and bats) and perform high wingbeat frequency flight. The low wingbeat frequency in some insects comes under the category of Neurogenic fliers and it usually ranges from 2 to 100 cps. The high wingbeat frequency in insects is known as Myogenic and ranges from 100 to 1000 cps. The neurogenic fliers are also known as synchronous fliers and the myogenic fliers as asynchronous fliers. The forward velocity is usually variable from 1 to 4 m per second and is influenced due to the small mass by the wind velocity. It is notable that when insects fly forward, their stroke plane also becomes more inclined forward

[3, 4]. The forward flight consists of a series of repeated downstrokes and upstrokes. The downstroke is a powerful stroke and the upstroke is more or less a recovery stroke.

(iii) **Gliding Flight**: Occasionally, insects are seen to glide with the wings outstretched. This is common in Odonata (Dragonflies), Orthoptera (Locusts) and Lepidoptera (Butterflies and Moths) which possess large wings. The ability to glide depends on the high Lift/Drag (*L*/*D*) ratio. *L*/*D* ratio changes with the angle of attack. This ratio is at a maximum for Lepidoptera with an angle of attack ranging from 5 to 15°. The wings of Lepidoptera are covered by scales that help in the development of lift but do not affect the drag because of their overlapping arrangement. Butterflies can glide for a longer duration because of the large wing area. During gliding, very little energy is spent. Locusts also practice long-distance gliding if the winds are favourable. Insects have been reported to be making effective use of thermal currents, more so in tropical areas and deserts. In the strict sense, it differs from true thermal gliding or soaring of birds as the insects are only carried passively by thermal currents during migration.

(iv) **Manoeuvring Flight**: Manoeuvrable flight is a self-correcting flight that enables the fliers in course correction and to overcome the obstacles coming in the flight path. Wings with a high aspect ratio, above 4, are more manoeuvrable. MAVs are usually designed with a relatively low aspect ratio of around 3, and hence, they are less manoeuvrable.

(v) **Passive Mode of Flight**: In addition to the above four modes of flight, a Passive mode of flight is possible for insects having relatively larger wings and with less powerful flying muscles. In the early stages of insect flight evolution, parachuting, gliding and passive flight might have played a greater role in their survival and small-distance passive migration when chased by a predator. The passive mode of flight is analogous to the falling of a leaf from the treetop. The passive flight may disturb the original flight plan of the flier including landing and take-off, particularly if there is any wind gust in the ambient. In passive flights, landing is always delayed depending on wind velocity.

Various researchers observed different mechanisms in the flapping motion of insects. One interesting kinematic mechanism has been occasionally a clap and fling type. Clap and fling is a flapping mechanism in which the wings come close together at the end of the upstroke above the body of the insect and meet dorsally. The downstroke motion starts with the wings moving away from each other and the clap is repeated at the end of each half stroke [6]. He suggested that the clap and fling mechanism helps in lift augmentation and it is based on kinematics of wing motion. The examples for clap and fling mechanisms are *Encarsia* and *Tessaratoma Javanica*. Steady-state aerodynamic studies usually apply to conventional aircrafts with fixed wings and a propelling mechanism.

Insect flapping flight is a highly complex one. The upward and downward flapping movements of the insect wings are controlled by different sets of flight muscles and occur with a small time gap in contrast to the motion obtained through a conventional linkage mechanism as in a flapping winged MAV. The angle of attack of the insect wing is much higher than that of a normal aeroplane because of the cyclic motion of the flapping flexible wings, which incidentally helps in the increased stall. Insects use different methods to enhance lift such as wake capture, rotational circulation (Magnus Effect) and delayed stall.

The aerodynamic forces on insect wings were predicted by using quasi-steady approach. In quasi-steady approach, the motion of the insect wings can be described in terms of a series of steady-state aerodynamic problems. C_L and C_D are time-invariant non-dimensional force coefficients and depend on lift-drag forces generated. In a flying insect, the wings encounter at each stroke quasi-steady flow conditions similar to those in the wind tunnel. Lift and drag can be estimated roughly throughout the stroke cycle from aerodynamic studies. The elementary blade approach integrates the force produced by each thin wing section, since wing velocity and wing chord change from wing root to the tip of the wing. These studies provide data both on wing velocity and angle of attack [7–9]. According to Ellington, quasi-steady assumption, the instantaneous aerodynamic forces on a flapping wing are equal to the forces in a steady motion, at an identical instantaneous velocity and angle of attack. This theory needs a careful reconsideration.

In the flapping wing motion of insect flight, unsteady aerodynamics plays a crucial role as it enhances both the lift and drag through wake capture, rotational effects and delayed stall. Thus, there exists a discrepancy in measurements made from direct force measurements as compared to quasi-steady state theory. However, time-invariant drag and lift studies in steady state help in finding out certain mechanisms of flapping flight to a preliminary level and they also help in estimating the unsteady effects [10]. Most of the studies on insect flight have neglected the Wagner Effect and focussed on unsteady effects [3, 4]. Flapping wings exhibit variable linear translatory and rotational (flapping) movements. Inertial bending of the wing, due to decreasing mass and small patches of resilin, adds to the complexity of wing kinematics. Our present knowledge of the aeroelasticity of insect flight is fragmentary.

The Principle of Lift and Thrust Generation by Flapping Wings

In the absence of energy input from the environment, the flapping wings of a flier in a steady flight must provide the necessary lift and thrust so as to maintain the required height and the forward speed. Therefore, it is essential to understand the complex kinematics of the flapping wing. In order to provide the necessary weight support, some symmetry has to be introduced into the pitching motion of the lifting surface. The symmetry can be obtained by just maintaining a constant angle of attack for the thrust generating wing. The easiest way for a flier is to tilt the whole body and the wings so that the beat plane describing the wing motion is inclined at an angle to the flight path.

The wings sweep forward during the downstroke if the angle of attack is not zero with respect to the wing root and backward during the upstroke. Therefore, the incident velocity and the geometric angle of attack are larger during the downstroke as compared to the upstroke. Thus, the resultant force is greater than the force which is produced during the upstroke. If the time taken for both the strokes is equal, the lift forces act in opposite direction and may cancel out, and the net lift may be nearly zero. In such scenarios, the flight may not be possible in biological and man-made fliers with flapping wings. The kinematics of the flapping wing is more complex and its proper understanding needs further study by using high-speed video for computing kinematics and Digital Particles Velocimetry (DPV) studies in advancing our understanding of insect bio-aerodynamics. Hence, more experimental work is necessary to understand the complexities of insect flight dynamics [3, 4].

Lift and Drag Coefficients

In the case of a body moving through a homogeneous fluid, the force may be communicated by the fluid through two basic mechanisms as mentioned below:

1. Pressure Distribution $p(s)$ and
2. Shear Stress Distribution $\tau(s)$ over the surface.

The resultant forces integrated over the whole surface are resolved into Lift component (L) of Force (F) normal to the free stream U and Drag component (D) of F parallel to Free Stream Velocity (U).

Dimensionless coefficients of lift and drag are denoted by C_L and C_D and can be represented by

$$C_L = \frac{L}{q_\infty S} = \frac{L}{\frac{1}{2}\rho V^2 S}, \tag{3.1}$$

and

$$C_D = \frac{D}{q_\infty S} = \frac{D}{\frac{1}{2}\rho V^2 S} \tag{3.2}$$

where

q_∞ is the Dynamic Pressure.
S is the Surface Area of the Wings.

Lift-Enhancing Mechanisms in Insect Flight

There are six additional lift-developing mechanisms. This has been reported to be operative in at least 20 types of insects after experiments by various authors.

1. Clap and fling mechanism
2. Wake capture (wing-wake interaction)
3. Passive pitching mechanism
4. Tip vortex formation and figure of eight (8)
5. Rapid pitching rotation and
6. Delayed stall of Leading Edge Vortex (LEV).

Such flight techniques are practiced by various insects, based on their specific requirements as well as on environmental conditions.

1. **Clap and Fling Mechanism**

   - The two wings together clap above and then fling them open apart in quick succession.
   - As a result of clap and fling action around each wing, circulation of air is enhanced for generating additional lift at a low Reynolds number.
   - Due to the clap action, there is a certain amount of damage to the dorsal structures as they come in contact with each other.

   Ex: Butterflies, Moths, Fruit Flies (Drosophila), Wasps, Thrips and Soapnut bugs.
   The importance of clap and fling is that it helps in generating additional lift and some thrust. The clap and fling mechanism is also exhibited by pigeons occasionally [6, 11]. Flying insects appear to increase their lift force by contralateral wing interaction during the clap and fling mechanism,however, this needs further study.
2. **Wake Capture (Wing-Wake Reaction)**: The wing is exposed to the wake region produced by the previous stroke in a flapping cycle. This mechanism is usually observed during a wing-wake interaction. This makes interaction with the wing during stroke reversal by the rotating wing and contributes to the lift production [12]. This is termed as wake capture. The wake capture helps in the aerodynamic lift by a transfer of momentum to the wing at the beginning of each stroke. The wake capture was considered as a lift-enhancing mechanism,that is, a wing can recover lift from fluid motion created in a previous half stroke [13]. Both the wing acceleration and the wing-wake interaction should be taken into consideration when modelling wing design.
   The fruitfly wing model may be taken as an ideal example of low Re flight. Wake capture force represents an unsteady phenomenon that involves changes in distribution and magnitude of vorticity during stroke reversal. It is interesting to remember that as compared to regular wing rotation, they exhibit enhanced downstroke contributing to aerodynamic loading [14].

3. **Passive Pitching Mechanism**: Three types of passive pitching modes have been recognized. 2-D flows and LEVs may help in additional attachment to flexible airfoils [15].
4. **Tip Vortex (TV) Formation**: In fixed finite wings, the wing tip vortices generally increase drag [16]. Once it was believed that wing tip vortices contribute to wastage of energy. However, in a flapping wing, the wing tip vortices may influence the total force exerted on the wing by creating a low-pressure area near the wing tip. In a flapping motion, the impact on aerodynamic forces by tip vortices is relatively less for wings having an aspect ratio of 4, adapted for delayed rotation [17]. It is quite possible that the wing tip vortices in a flapping wing do influence lift and thrust.
The vortices associated with fixed finite wing appear to decrease lift and drag. It may stabilize the shed vortices and this involves non-linear interactions. However, for a low aspect ratio flapping wing, the impact of tip vortex may not be significant [18].
5. **Rapid Pitching Rotation**: In a flapping cycle, an insect wing carries out both translational and rotational motions. The Kramer effect states that the coupling of wing rotation with translational motion has aerodynamic advantages. An increase in the angle of attack during translation may increase lift above steady-state values and is closely related to delayed stall at higher angles of attack.
The rotational forces are caused by the flapping wing and the same fluid dynamic mechanism happens during wing translation [19]. Magnus effect is rather applicable to cylinders and spheres. However, biological wings have a sinusoidal action. Hence, the significance of the Magnus effect cannot be ruled out. The Kramer effect describes the rotational forces [3, 4. Therefore, LEV is the only force generating the aerodynamic phenomenon in the flapping cycle and the rotational effect may not contribute much to it [20]. There is also an increase in the vorticity pattern around the wing due to rapid pitch-up rotation. This helps in increasing the lift [17].
6. **LEV and Delayed Stall**: One of the significant characteristics of an insect wing is that in real time flow insect wing produces more lift as compared to a wing in a wind tunnel [10]. Generally, the wings of an aeroplane stall and lose lift rapidly beyond an angle of attack of 15° depending on the type of aerofoil. In contrast, insect wings can sustain a maximum angle of attack of 45° in a flapping cycle. The flow does not follow the contour of the wing and leading edge vortices are developed, which contribute to the lift (Fig. 2.1). This development of lift force is due to the presence of smaller viscous forces than pressure forces which are associated with fluid velocity. The flow separation takes place from the upper surface. This LEV forms a low-pressure area above the wing resulting in enhanced lift. The LEVs sustain a balance between the pressure gradient, the centripetal force and the Coriolis force 17. Diagrammatic representation of LEV has been shown from the source for a better understanding (Fig. 3.1). A leading edge vortex is larger than a stable separation bubble which remains attached to the upper surface of the wing at a higher angle of attack and at a low Reynolds

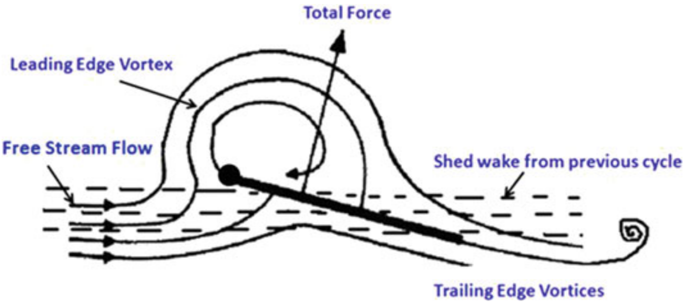


Fig. 3.1 Flow Structures in the Formation of LEVs along the Wing span (Modified and redrawn from various sources)

number [21]. This leading edge vortex is a low-pressure region, and it increases the lift by 80%.

Ellington et al. [22] observed that delayed stall of leading edge vortex (LEV) can significantly enhance the lift associated with a normal flapping wing. The exact role played by the LEV and its consequences on lift generation remain to be elucidated fully. Leading Edge Vortex (LEV), Trailing Edge Vortex (TEV) and Tip Vortex (TP) play an important role in effecting the delayed stall. It is interesting to note that LEV generates a lower pressure area which in turn increases the suction force on the upper surface of the wing. Formation of LEV is a general flow feature in flapping wings having Re of 10^4 or less. Changes in Re number reduce the frequency, and the Strouhal number will affect delayed stall with an increase in frequency.

It is the airflow separation from flying aeroplane wing relatively at higher angles of attack resulting in a sharp fall in lift and increase in drag leading to a serious aircraft accident. Flow separation infers the separation of the boundary layer which is in contact with the surface of an aeroplane. The stall angle limit in aeroplane ranges from 15° to 16°. However, for insects, it is variable from 45° to 90° (Fig. 3.2). The elastic nature and structural deformation of the wings and relatively high frequency of the wingbeat help in enhancing the stall angle in insects. In biological fliers, the pre-stall may continue for some time and this helps in quick recovery due to fast feedback sensory systems prevalent in insects.

Aerodynamics of Insect Flight

The insects mostly depend on Leading Edge Vortices for lift generation. These vortices create a spiralling motion of air along the leading edge. A flapping wing of an insect moves through two basic half strokes. The downstroke starts up and slightly backs so that the insect is plunged downward and moves forward. Immediately, the wing is flipped over (supination: downstroke to upstroke) so as to make the leading edge pointed backward. Sane [3, 4 emphasized the importance of the stability of

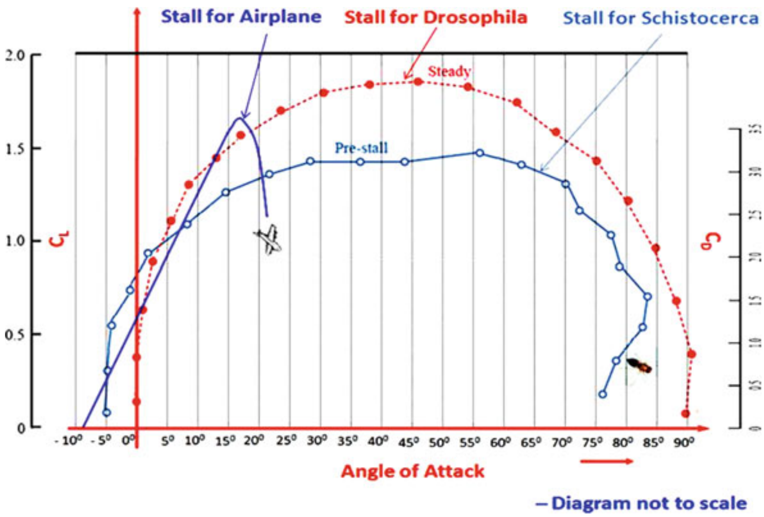
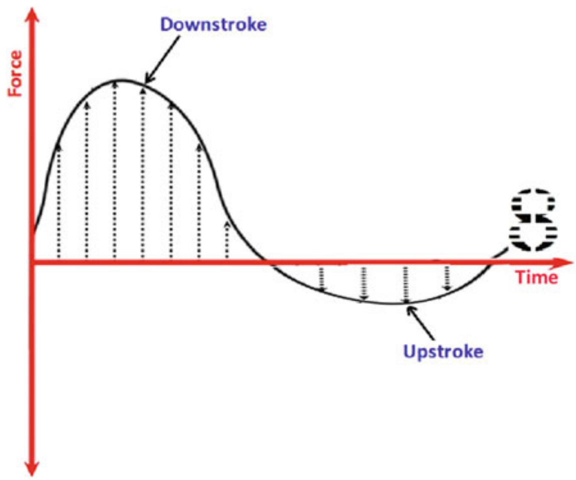


Fig. 3.2 Stall in an insect and aeroplane (Modified and redrawn from various sources)

leading edge vortex at high angles of attack. This in turn helps the insect to generate additional force by the wing and helps to hover. During upstroke, the wing is pushed upward and backward followed by a pronation (upstroke to downstroke) so as to allow another downstroke (Fig. 3.3). The term *wing rotation* during these two types of strokes refers to the changes in the angle of attack around a chordwise axis. Hence, the calculations of aerodynamic forces during an insect flight appear to depend on the theories based on wing rotation in different insect species.

Fig. 3.3 Forces acting on a flapping wing during downstroke and upstroke



The insect wingbeat frequencies are variable from synchronous (2–100 Hz) to asynchronous frequencies (100–1000 Hz) as mentioned earlier. During hovering, upward stroke time slightly increases compared to that in normal flight, but still about 10–15% less than downstroke time. The lift generated during each wingbeat cycle is more or less equal to the weight of the flier.

The effects on a flapping wing can be summarized into three major aerodynamic phenomena as follows:

- Leading edge vortex
- Steady-state aerodynamic forces on the wing and
- Wing interaction with its wake from previous strokes (wing-wake capture reaction).

Generally, the weight of many flying insects ranges from 20 μg to 150 g. The Reynolds number (*Re*) also changes from insect to insect and will be proportional to the size of the insect. For smaller insects, it will be as low as 10 and may increase to a value of 10^4 based on the size of the insect and the velocity of the flier. Low *Re* values of insects play a vital role in understanding insect flight and may contribute better in inferring its flight design. In this flight regime, the flow physics is not fully understood. A thorough knowledge of the flapping wing dynamics is vital in the appropriate design of the bio-mimicking MAVs.

The Governing Equations for an Insect Flight

Considering a wing cross section, the force component normal to the flow direction can be named as lift (L) and the force component acting along the flow direction is a drag (D). The lift and drag components (Fig. 3.4) can be expressed as follows.

$$L = \frac{1}{2}\rho V^2 S C_L \tag{3.3}$$

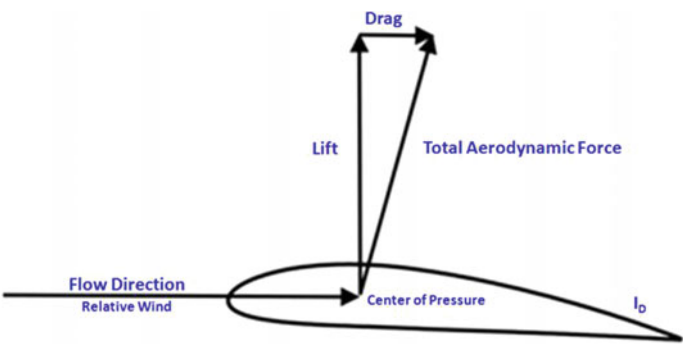


Fig. 3.4 Aerodynamic forces on an airfoil

$$D = \frac{1}{2}\rho V^2 S C_D \tag{3.4}$$

where

C_L and C_D are dimensionless and denoted as coefficients[1] of lift and drag.
ρ density of air.
V Velocity of the insect.
S Area of the two wings.

In an insect, the wing profile shape and viscosity of air influence the amount of total drag on the wing, which in turn develops a certain amount of lift depending on the Angle of Attack (AOA, $\propto$) [23]. The insect wings are thin chitinous membranes. Hence, the non-dimensional coefficients of lift and drag (i.e. C_L and C_D) are the functions of AOA.

From Eq. 3.3 and 3.4, we get

$$\frac{C_L}{C_D} = \frac{\left(\frac{2L}{\rho V^2 S}\right)}{\left(\frac{2D}{\rho V^2 S}\right)} = \frac{L}{D}. \tag{3.5}$$

However, by considering the balance between lift and weight during steady state, we can write $L = W$, and also by considering the surface area (S) of the wing over a functional parameter, we can write

$$\frac{L}{D} = \frac{W}{S \times K}, \tag{3.6}$$

where K is the specific resistance value for individual species. The value of K depends on the surface pattern/texture of the wing, wing position and angle of attack; thus, this may be considered as a species-specific character. However, to know the exact values of K, we need further experimental studies.

The flow around the insects is considered to be incompressible for which the Mach number will be less than 0.3 and hence, there is no density variation and ρ is considered to be constant. Considering the Navier–Stokes equation subjected to no-slip boundary conditions, we can write

$$\frac{\partial u}{\partial t} + (u.\nabla)u = -\frac{\nabla p}{\rho} + v\nabla^2 u \tag{3.7}$$

$$u.\nabla = 0 \tag{3.8}$$

$$u_{bd} = u_s \tag{3.9}$$

[1] A coefficient can be considered as a number or symbol with a variable or unknown quantity.

where

$u(x, t)$	The Flow Field.
p	Pressure.
ρ	Density of Fluid.
∇	Del Operator.
μ	Dynamic Viscosity.
ϑ	Kinematic Viscosity.
u_{bd}	Velocity at Boundary condition.
u_s	Velocity of the solid.

The Navier-Strokes equation in a non-dimensional form describes how the velocity, pressure and density of a moving fluid are related. Hence, it comes out to be a useful phenomenon to understand the insect flight under various dimensions. The equation is non-dimensional and the airflow is incompressible.

A non-dimensional form of equation with Reynolds number (*Re*), wing length (l) and velocity (V) can be expressed as

$$Re = \frac{\text{Intertial Forces}}{\text{Viscouse Forces}} = \frac{\rho V L}{\mu} = \frac{V L}{\vartheta}$$

$$\frac{\text{Total Momentum Transfer}}{\text{Molecular Momemtum Transfer}} \tag{3.10}$$

Compared to an airfoil, the insect wing is very small and it also flaps with high frequency during flight. The range of Reynolds number in most of the insect flights varies from 10 to 10^4. For small insects, the Reynolds number will be very low and increases proportionally with the increase in the insect dimensions (Table 3.1).

A dragonfly with a mean wing chord of 1 cm, wing length 4 cm and wingbeat frequency of about 40 Hz with tip speed (u) as 1 m/s operates at a Reynolds number, $Re = \frac{uc}{\vartheta} = 10^3$. However, *Chalcid wasp* with a wing length of 0.5–0.7 mm with a wingbeat frequency of about 400 Hz operates at a Reynolds number of 25 [24]. On the other hand, a bigger insect like *soapnut bug* (*Tessaratoma javanica*) with wing length of 2.2 cm and a chord length of 1.15 cm has a wingbeat frequency of 50 Hz and is having a Reynolds number of above 4000. Similarly, for a *Pentatomid bug* (*Chrysocoris purpureus*), the wing length is 1.2 cm and chord length is 0.65 cm, has

Table 3.1 Flight parameters and *Re*

S. No	Insect	Wing Chord (B_{eff}) in (cm)	Wing length (cm)	ϑ_h (Hz)	*Re*
1	Dragonfly	1	4	40	40
2	Chalcidwasp		0.5–0.7	400	25
[a]3	T. javanica	1.15	2.2	50	> 4000
[a]4	Pentatomoid bug (CP)	0.65	1.2	90	1000

[a] The compilation of data from various sources

a wingbeat frequency of 90 Hz and is having a Reynolds number of 1000 (Chari, N—Personal Communication).

In an insect, the wing will have three velocity scales which lead to two more dimension less parameters (U_0/u) and ($\Omega c/u$) along with the Reynolds number. Here, u is flapping wing velocity with respect to insect body,U_0 is forward velocity of the body and Ωc is pitching velocity. U_0/u is also known as the advance ratio, which is also related to reduced frequency fc/U_0 [24].

By considering a relatively rigid non-flexible insect wing (viz., Drosophila), the motion of the wing is relative to the fixed body, which can be explained by three variables [24].

(a) Position of the tip in spherical coordinates $\Theta(t)$ and $\Phi(t)$ and
(b) Pitching angle $\Psi(t)$, which is above the axis connecting root and tip.

The role of AOA, α, is vital to calculate the aerodynamic forces, which ranges from 25° to 45° for hovering insects. The role of the Angle of Attack (AOA) is vital to calculate the aerodynamic forces. The AOA ranges from 25° to 45° for hovering insects with a high wing span. Most of the insects hover to stay at one spot in the air by flapping their wings rapidly. Though this process of hovering is complex, the insects need to stabilize and need to overcome the body weight due to gravitational force for required lift. The lift forces on the wings during upstroke are small and during downstroke, the forces on the wings will be high, and due to which, the insect moves up and down oscillating to keep itself in the same position. The wingbeat frequency of an insect to maintain stability and amplitude can be calculated by making reasonable assumptions as suggested by [25]:

- Lift force to be a constant when the wings are moving down; which means that the force during upstroke is very less.
- The insect drops by a distance h due to gravity during upstroke for a time interval Δt.
- And h will be equal to $h = \frac{g(\Delta t)^2}{2} = 0.1$ mm (typical).
- The maximum allowable time (Δt) can be calculated for the free fall of the insect as

$$\Delta t = \sqrt{\left(\frac{2h}{g}\right)} = \sqrt{\frac{2 \times 10^{-2}}{980}} \approx 4.5 \times 10^{-3}\ \text{s}.$$

- By considering *Stroke Period* (T) for a cycle of insect flight including both up and down movements, we get $T = 2.\Delta t = 9 \times 10^{-3}$ s or 9 ms.
- The wingbeat frequency per second can be calculated by $\vartheta = f = \frac{1}{T} \approx 110\,\text{Hz}$.

The wingbeat frequency of insects ranges from 4 to 1000 Hz. Davidovits [25] explained the important relation between *upward force* and *insect body weight* to restore the insect's original position. However, it has to be mentioned that the average upward force on the flying insect is equal to its weight ($L = W$).

The power required for maintaining hovering to lift the insect body weight against gravitational pull can be calculated and average force $\left(F_{\text{avg}}\right)$ needed for two wings during downstroke is also two times that of an insect weight (i.e. $F_{\text{avg}} = 2W$). Generally, the pressure applied by the wing will be uniformly distributed over the total wing area and hence, the force generated by the individual wing will be acting on a single point (i.e. at the midsection of the wing). Total work done during downstroke (wings traverse to a vertical distance d) can be given as

$$\text{Work} = F_{\text{avg}} \times d = 2Wd. \tag{3.11}$$

Work also means a force should move an object in the direction of the force. The component of the force in the direction of the movement does any work.

As an example by considering an insect weighing 100 mg (0.1 gm) with wings of 1 cm long, vertical distance d as 0.57 cm, we get the work done by two wings as equal to Work $= 2 \times 0.1 \times 980 \times 0.57 = 112$ erg. Now we can calculate the energy required by an insect with mass 0.1 gm to raise by a height of 0.1 mm during downstroke which is given by $E = mgh = 0.1 \times 980 \times 10^{-2} = 0.98$ erg.

The results obtained here show that the energy spent for a downstroke is almost negligible and the maximum share of the energy developed due to downstroke is converted into kinetic energy.

The calculation of power required by the wing per second can be calculated as an output power,

$$P = 112 \text{ erg} \times 110\left(\text{s}^{-1}\right) = 1.23 \times 10^4 \frac{\text{erg}}{\text{s}} = 1.23 \times 10^{-3} \text{ Watts } [1\text{w} = 10^7 \text{ ergs/s}].$$

Considering the rotary motion of the insect wing, the kinetic energy of the flying insect during each stroke is given by

$$KE = \frac{1}{2} I w_{\max}^2, \tag{3.12}$$

where

I is the mass moment of Inertia of the wing.
$w_{\max}$ is the maximum angular velocity during each wing stroke.

Here moment of inertia of the wing will be given by

$$I = \frac{ml^2}{3}, \tag{3.13}$$

where

l is the length of the wing;
m is the mass of the wing ($\approx 10^{-3}$ g)

A general expression for Moment of Inertia is given by

$$I = \sum_{i=1}^{n} m_i r_i^2, \tag{3.14}$$

where

m_i is the mass of i strip of the wing in grams.
r_i is the distance between the fulcrum and centre of i strip.
n is the strip number.

The maximum angular velocity ($w_{\max}$) is calculated from maximum linear velocity ($v_{\max}$) at the centre of the wing.

$$w_{\max} = \frac{v_{\max}}{l/2}. \tag{3.15}$$

Average linear velocity can be calculated at the centre of the wing for a distance d traversed at the centre of the wing divided by duration Δt during each wing stroke. For the above example with $d = 0.57$ and $\Delta t = 4.5 \times 10^{-3}$s, the average linear velocity is calculated as

$$v_{\text{avg}} = \frac{d}{\Delta t} = \frac{0.57}{4.5 \times 10^{-3}} = 127\,\text{cm/s}.$$

At the beginning and end of the wing strokes, the velocity of the wings will be zero and by assuming a sinusoidal variation of velocity along the wing path, the maximum velocity of the insect will be twice and it will be as high as the average velocity. Hence, the maximum angular velocity (from Eq. 2.15) is given by

$$w_{\max} = \frac{254}{l/2}.$$

And the kinetic energy from Eqs. 2.12, 2.13 and 2.15 is given by

$$KE = \frac{1}{2} I w_{\max}^2 = \frac{1}{2}\left(\frac{10^{-3} l^2}{3}\right)\left(\frac{254}{l/2}\right)^2 = 43\text{ erg}.$$

The KE for both (up and down) strokes of a cycle of wing movement is $2 \times 43 = 86 ergs$. It is possible to apply these formulae for smaller pentatomids such as ***Chrysocoris purpureus***.

Resilin

The wing joints of insects contain a pad of elastic (rubber-like) protein called as ***resilin***. It helps insects in moving their wings in upward and downward directions. During upstroke, resilin is stretched and KE of the wing is converted into potential energy. During the downward position of the wing, energy is released which helps in completing the downstroke.

Insects will gain *KE* during the acceleration by the contraction of the flight muscles. During deceleration at the end of the stroke, energy must be dissipated and *KE* will be converted into heat energy. Sometimes, this heat will be utilized by the insects to maintain their core body temperatures.

Based on some simplified assumptions, the amount of energy stored in the resilin can be calculated. In reality, the resilin will be bent into complex shapes. However, in this case, it is considered as a straight rod with area A and length l.

Considering resilin obeying Hooke's law, which in general is not exactly true as resilin is stretched by a considerable amount, considering area and Young's Modulus do not change in the process of stretching, the energy E stored in resilin can be estimated as below [25]:

$$E = \frac{1}{2}\frac{YA\Delta l^2}{l}, \tag{3.16}$$

where Y is Young's Modulus for resilin ($\approx 1.8 \times 10^7$ dyne/cm^2).

Typically for a honey bee weighing 0.1 gm, the stored energy in the two wings was calculated to be 40 ergs approximately, where the value of Δl is about 10^{-2} cm. Similar values can be calculated for plant bugs and carpenter bees which weigh above 1 gm. A further discussion on resilin and the relevant equations is given in Chap. 8.

Actuator Disc Concept (Disc Area Concept)

The actuator disc theory is the oldest mathematical representation of a propeller or a wind turbine. This concept was first developed for evaluating ship propellers by Rankine in 1865 and Froude in 1885. Later on, Betz in 1926 developed a simple model of actuator disc concept for turbine rotors. 'Actuator Disc Theory' is also known as 'Momentum Theory'. The analysis of the aerodynamic behaviour of rotary wings, wind turbines and flapping wings can be started by considering the energy extraction process, without any specific design considerations. Froude derived the energy balance as "the work done by the disc equal to the thrust times the velocity through the disc, which in turn equals mass flow times the change in velocity". Therefore, the velocity at the disc is the average of the velocities for upstream and downstream flows (Fig. 3.5).

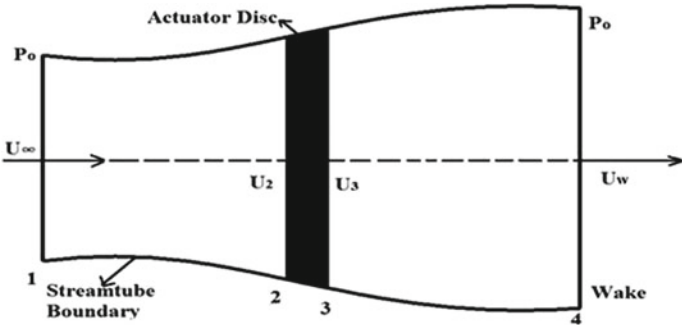


Fig. 3.5 Schematic diagram of stream tube boundary

The actuator disc model is based on the following assumptions like no frictional drag, homogeneous, incompressible, steady-state fluid flow and pressure variation or thrust per unit area over the disc, continuity of velocity through the disc and the infinite number of blades. The idealized actuator disc concept has been used by many entomologists for understanding hovering in insects.

Applying conservation of linear momentum across the disc,

$$T = \dot{m}(U_\infty - U_w). \tag{3.17}$$

Applying energy balance across the disc using the Bernoulli equation

$$P_d + \frac{1}{2}\rho U_R^2 = P_o + \frac{1}{2}\rho U_w^2, \tag{3.18}$$

$$P_o + \frac{1}{2}\rho U_\infty^2 = P_o + \frac{1}{2}\rho U_R^2. \tag{3.19}$$

By solving the above equations for thrust on the actuator disc, power output of the rotor can be evaluated. Finally, performance parameters such as power coefficient (C_P), thrust coefficient (C_T) and the tip speed ratio (λ) of a rotating wing can be expressed in a dimensionless form which are given as

$$C_P = \frac{2P}{\rho U_\infty^3 \pi R^2}, \tag{3.20}$$

$$C_T = \frac{2P}{\rho U_\infty^2 \pi R^2}, \tag{3.21}$$

$$\lambda = \frac{R\Omega}{U_\infty}, \tag{3.22}$$

where

U_∞ is free stream velocity.
P_o is free stream pressure at stations 1 and 4.
U_2 is the velocity at the upstream of the actuator disc.
U_3 is the velocity at the downstream of actuator disc.
U_w is the velocity in the wake region.

Actuator Disc Model for Flapping Flight

The calculation of induced power for flapping flight comes basically from the helicopter theory rather than a fixed-wing theory. A helicopter rotor sweeps out a circular disc, which can be considered as an 'Actuator Disc Model', which states that air pressure increases in a stepwise manner when the air passes through the disc. This increase in air pressure imparts a downward velocity to a tube of air that flows through the disc. The cross section of the tube is the diameter of the rotor in the case of helicopter and wing span in the case of an insect wing. The wings of insects do not cover the full disc area due to the limitation of stroke angle; however, the induced power is calculated based on this actuator disc model. The actuator disc concept helps in calculating the induced power during hovering. The methodology has been outlined by Chari [26].

The following advantages are observed when the actuator disc concept is applied for flapping wing flight which is termed as 'Bow-Tie':

1. The approach does not require information about the wing structure or wing mass except the wing span.
2. Local airspeed is assumed to be uniform all along the wing span, which permits a clear simplification considering rotary or flapping wings.
3. The calculation does not require the angle of flapping except the wing area through which air passes as it is accelerated downward.
4. Some authors have used wing swept area instead of full circles for calculation of induced power, as the bird or insect flaps its wings in less than 70°, a relatively narrow swept area is formed.

This bow-tie concept may not hold good when lifting line theory is considered for lift generation and induced velocity calculations.

Prandtl's Vortex System

It has been explained earlier that only by circulatory flow, the lift is generated by proper vortex strength. The German scientist Prandtl [27] postulated the three-dimensional wing theory and proposed that the actual wing could be replaced mathematically by a vortex filament. A similar concept was proposed earlier by English engineer FW Lanchester simulating the wing with the help of a vortex line. Prandtl simulated the wing by properly placing vortex filament and called this as a bound vortex or vortex lifting line. This can also be termed as bound vortex as it is especially bound to the inside of the wing. The bound vortex with its infinite velocity does not exist in the fluid. The fluid surrounding the wing behaves as if the vortex is really there. Prandtl further realized that the Helmholtz vortex laws were applied as if the bound vortex really existed. With reference to the theorem (1) of Helmholtz, the bound vortex would not disappear when the lift drops down to zero at the wing tips. With reference to theorem (2), the free vortices could have the same strength as the bound vortex. From the theorem number (3), the vorticity would remain attached to the same air particles initially present at the wing tip and, therefore, would trail behind the flying object [26].

From the above considerations, these vortices are termed as trailing vortices and in a steady motion would trail downstream to infinity. This pattern of trailing vortices was named as horseshoe-shaped vortices by Prandtl. From the direction of the circulatory flows as required for producing lift, it can be summarized that the effect of trailing vortices is to produce the downward flow of air behind the wings. This flow is called as 'downwash'. The trailing vortices and the flow field they create, particularly the downwash, have profound effects on the flight performance and stability of the flier. This is also called Prandtl's Horseshoe Vortex System. A biological wing could be represented by a vortex system for understanding the flow patterns.

Summary

From the literature survey, it can be seen that many aspects like lift production, the effect of the body and the planform shape influence the aerodynamic performance of an insect flight. Insect flight aerodynamics involves a combination of quasi-steady and unsteady aerodynamic phenomena which play an important role in the manifestation of the insect flight. More experimental and theoretical studies with suitable simulation experiments are necessary to understand the complexities of insect flight. These studies will also help in the design of the wings for the man-made MAVs.

The different aspects of Insect wing aerodynamics covered in this chapter can briefly be summarized as follows.

1. Insects are among the first class of invertebrate fliers which differ phylogenetically, morphologically and structurally from vertebrate fliers (birds and bats). However, all these fliers develop similar aerodynamic forces needed for flight by moving wings during flight and these diversified wings are analogous structures.
2. Insects exhibit their flight style involving complex wing movements such as flapping, twisting and to-and-fro oscillatory motion. They can perform hovering, gliding, forward flight (flapping), manoeuvring and passive flight as per their biological needs dictated by various environmental factors.

3. Insects fly at low Reynolds numbers ranging from about 1 to 10,000 where viscous effects, boundary layer flow separation and vortex formation are predominant.
4. Various lift generating mechanisms in insect flight include wake capture, passive pitching mechanism, tip vortex formation, rapid pitching rotation, clap and fling mechanism and LEV helping in the delayed stall.
5. By virtue of wing and body movements, insects can prolong their pre-stall zone of operation up to an angle of attack, AOA, of nearly 90°. The stalling angle for an aeroplane wing, however, is limited to 15–20°. It may be relevant to mention that the pre-stall period extends over an AOA of 40–75°, typically, helping in effective stall recovery through integrated sensory feedback mechanism resulting in synchronous complex wing motion.
6. The insect gets its lift basically from a powerful downward stroke, while the upward stroke is more or less a recovery stroke with marginal or very little lift generation.
7. The wingbeat frequency of flying insects covering neurogenic (synchronous) and myogenic (asynchronous) types are about 2 to 100 Hz for the former and from 100 to 1000 Hz for the latter. If wings are mutilated, the ϑ_h increases in the myogenic fliers.
8. Many insects, because by virtue of their low mass and relatively large wing area, try to float in the air (like a fish in the water) while flying.
9. They are able to withstand the muscle fatigue from the continuous flapping of wings through the presence of resilin, an elastomere protein at the wing base.

The actuator disc concept may be effective in calculating induced power in hovering and may help in understanding the design for flapping wings of hovering Insect mimicking MAVs.

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Chapter 4
Flight Morphology and Flight Muscles

N. Chari, A. Ravi, Ponna Srinivas, and A. Uma

Abstract Structure of flying segments—thorax, associated chitinous membranous wings and their morphology have been explained including venation. Venation of wing helps in identifying species and also in classifying insects. Direct and indirect flight muscles, which help wing movements have been described. Flight parameters of body and wing contribute to basic understanding of wing movements in insect flight. Flight parameters of some insects have been studied in greater detail so that this may help in understanding the design of biomimicking MAVs. Differences between Neurogenic and myogenic muscles and the basis of muscle contraction have been explained. Oxidation of biomolecules has been summarised in the form of a table.

Keywords Wing venation · Wing muscles · Flight parameters · Wingbeat frequency · Pterothorax · Myofibrils · Neurogenic and myogenic fliers

Introduction

The study of the flight morphology of insects helps in understanding basic and derived flight parameters which are responsible for the flight performance of a flier. In insect flight, the mass is small and the aerodynamic forces such as lift, thrust and drag developed are proportional to wing area and wingspan. The morphological parameters of the insect body and associated wings help in flight. Basic flight parameters and their development are under genetic control. Therefore, the detailed study of basic and derived parameters and their correlation is necessary to understand the aerodynamic

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forces of insect flight. Biological flight is highly complex and still remains to be elucidated fully; hence, the research is being carried out in different laboratories [1].

Structure of Thorax and Wing Morphology

The insect body is differentiated into three distinct regions such as head, thorax and abdomen as shown in Fig. 4.1. The thorax is considered as a locomotory apparatus having three pairs of legs ventrally and two pairs of wings laterally for flight. A detailed description of the morphology of insect thorax has been documented after [2] and others [1].

Thorax has three segments: prothorax (pro is first), mesothorax (meso is second) and metathorax (meta is third). Prothorax has no wings. However, meso and metathorax have a pair of lateral flying wings which are known as the first and second pair of flying wings. The dorsal portion of the thorax is covered by a sclerite which is known as tergum. While the V-shaped ventral portion covered by a plate is known as the sternum and the lateral portion (where tergum and sternum meet) is called as pleuron. The pleuron forms the semi-elastic lateral wall of the thorax and surrounds the base of the leg. Each of the thoracic segments has a pair of legs ventrally. Insects are also named as hexapoda since they possess six legs as compared to spiders, millipedes, centipedes and crabs.

The wings are thin chitinous membranes attached to the sides of the thorax by an elastic membrane (resilin). Each wing has a geometric structure and is traversed by longitudinal veins, which support the membrane and contribute to the flapping flexible behaviour of the wing resulting in the lift, thrust and drag due to aeroelasticity and structural deformation of the wing.

Each segment of pterothorax (flying segments) has a pair of parallel muscles running longitudinally below the tergum. They also have a pair of vertical muscles connecting the sternum to the tergum, which help in up and down movements of the wings indirectly. Thorax also has other muscles attached to the base of the wings for effective turning/rotation of the wings when the insect is flying. During the rest time,

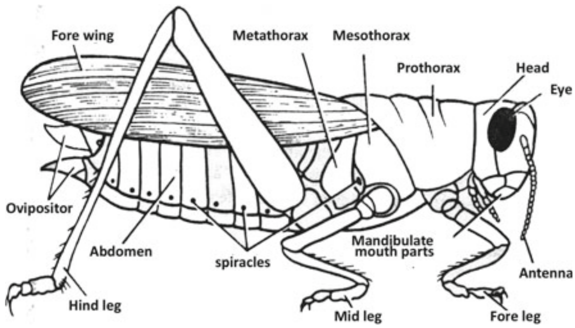

Fig. 4.1 Outline features of Grasshopper (a typical insect)

the wings are usually folded on the back and the body rests on three pairs of jointed legs on the substratum.

The main flight muscles in the thorax can be classified as direct and indirect flight muscles. Direct flight muscles are present in primitive insects and are attached to the wing base directly. Hence, they can move their wings by contraction either downward or upward. However, in insects with indirect flight muscles, the wings are attached to the thorax and by their contraction, they deform the thorax. As the wings are the continuation of thoracic chitin, the contraction of the flight muscle causes the deformation of the thorax which in turn leads to down and up movements of the wings which usually trace a figure of eight.

Based on the number of contractions made by the thoracic muscles, we have low-frequency and high-frequency fliers. Low-frequency fliers are known as neurogenic (synchronous) and high-frequency fliers are known as myogenic (asynchronous). Flight motor construction in insects has evolved independently. Wing venation also might have evolved from a single ancestor. The study of flight morphology helps in understanding the body and wing geometry, scaling laws, mimicking models, wingbeat frequency and flight at low Reynolds number at a moderate velocity.

The Vein

Each of the wings consists of a thin membrane supported by many longitudinal veins. The membrane is formed by two layers of integument closely fused, while veins are formed where two layers remain separate and the lower cuticle is thicker. Within each of the major veins, there is a nerve and trachea. Since the cavities of veins are connected with the haemocoel, haemolymph (the colourless blood) can flow into the wings from the base of the wing to the tip of the wing (Fig. 4.2).

The Transverse Section (TS) of the longitudinal vein of the wing has a covering of wing membrane running along the epidermis. The study of Fig. 4.2 shows the cut

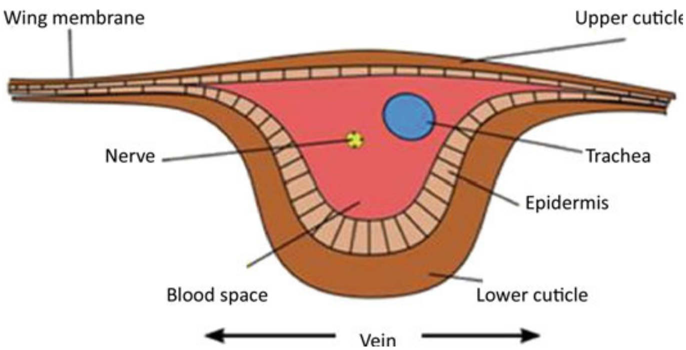

Fig. 4.2 Transverse section of a longitudinal vein (illustrative)

trachea and nerve floating in blood space. This clearly indicates that the insect wing is a living membrane covered by a cuticle on both sides.

Wing Venation [3]

1. In small insects, the venation is greatly reduced as in chalcid wasps.
2. In the wings of grasshopper and crickets, branching of the veins produces accessory veins or intercalary veins between the original veins.
3. Large numbers of cross veins are found in dragonflies and damselflies forming a reticulum.
4. All winged insects are supposed to have evolved from a common ancestor, the "archedictyon". The hypothetical scheme of wing venation represents (Fig. 4.3) the "template" that has been modified by natural selection for more than 200 million years in different orders of insects.
5. Wing venation helps in the classification of insect orders which is listed below in Table 4.1.

The basic longitudinal veins which can be distinguished from the leading edge of the wing are shown in Figs. 4.3 and 4.4. The veins are named after the Comstock–Needham System.

The wing also has some folds. The wing venation helps in the classification of insects and contributes to the aeroelastic properties of the wing in flight. The geometry of the wing is variable in many orders. The fundamental basic plan of

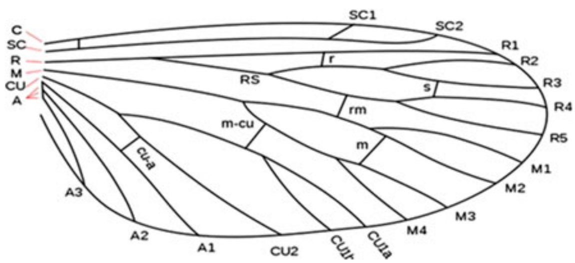

Fig. 4.3 Wing venation (The Comstock–Needham System)

Table 4.1 The classification of veins

Costa	(C)	First longitudinal vein, the leading edge of the wing
Subcosta	(Sc)	Second longitudinal vein (behind the Costa), typically un-branched
Radius	(R)	Third longitudinal vein, one to five branches reach the wing margin
Media	(M)	Fourth longitudinal vein, one to four branches reach the wing margin
Cubitus	(Cu)	Fifth longitudinal vein, one to three branches reach the wing margin
Anal veins	(A_1, A_2, A_3)	Un-branched Veins behind the cubitus

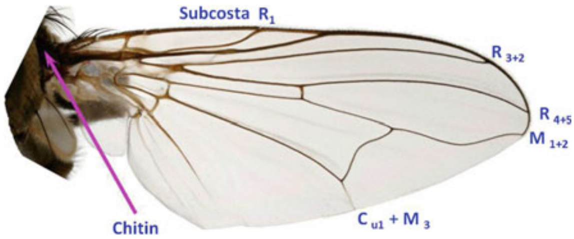

Fig. 4.4 Wing and venation of a housefly

the wing venation has been shown in Fig. 4.3 and that of a housefly which differs significantly in Fig. 4.4.

Wing Joints

1. A majority of insects can flex their thin wings over the back when at rest.
2. There is a complicated articular structure at the wing base than a mere hinged joint of the wing with the body.
3. Each wing is attached to the body by a membranous basal area. The membrane contains a number of small articular sclerites, collectively called "pteralia".
4. Pteralia includes a group of "axillaries" which are specially developed only in the wing flexing insects.
5. The axillaries contribute to the flexor mechanism. There are first, second and third axillary sclerites that support the wing.
6. There are special sclerotized plates such as humeral plate at the base of the costal vein, distal plate at the base of the cubic vein and proximal plate at the base of anal veins, and thus, it supports the venation of the wing (Fig. 4.5).

Wing Muscles

1. The insect flight muscles are highly oxidative in their metabolism and constitute 10–30% of total body mass.
2. Insect muscles are strictly aerobic and maintain high levels of energy required during flight. Fuel is carried by the blood to the muscles and O_2 through minute tracheoles by diffusion. Flight muscles have many mitochondria which act as miniature powerhouses of the cells.
3. Many wing muscles are large measuring about 10 mm in length and 2 mm in width.

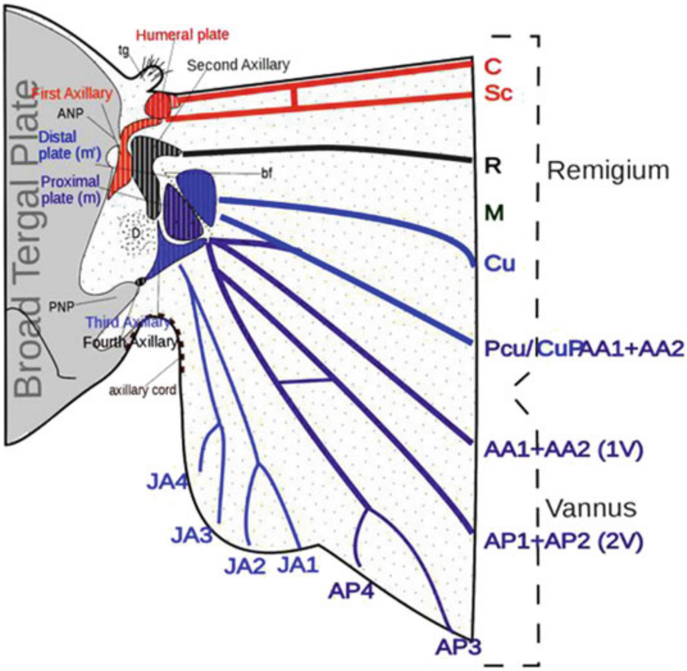

Fig. 4.5 Wing joints of an insect

Direct Muscles

In all insects, the upward movement of the wings is due to the contraction of indirect dorsoventral muscles or vertical muscles. As a result of this contraction, the wing membrane moves up and with the pleural process act as a fulcrum. These muscles may not be always homologous in different insect groups. Direct Flight Muscles are found typically in Odonata (Dragonfly) and Blattaria (Cockroach) (Fig. 4.6).

Indirect Muscles

The up and down movements of the wing are produced by indirect muscles due to changes in the shape of the notum (tergum plate), which is not directly attached to the wing base. Indirect Flight Muscles are typically found in Diptera (Housefly) and Hymenoptera (Honey bees). The wing movements, Transverse Sections (TS) and structure of thorax are shown in Figs. 4.7 and 4.8 in a semi-diagrammatic fashion modified from various sources.

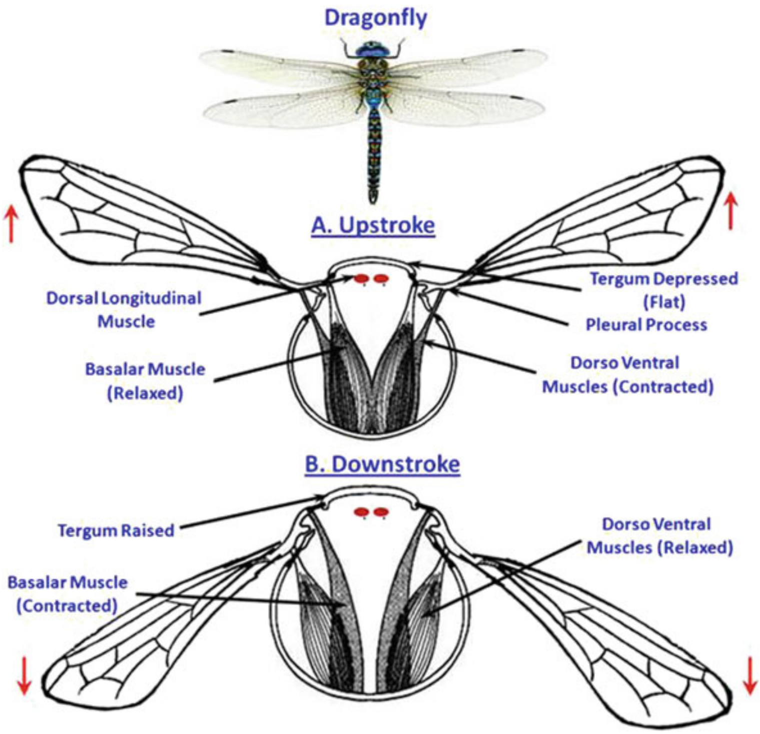

Fig. 4.6 Illustrating the direct muscle action in an insect

Wing Coupling, Folding and Wing Movements

1. In many insect species, the fore and hind wings are coupled together on each side, which improves the aerodynamic efficiency of flight.
2. In Hymenoptera (Bees and Wasps) and Trichoptera (Caddis flies), a row of small hooks called “hamuli” located at the front margin of hind wings lock on to the forewing; thus, both the wings are held together.
3. In some other insects such as butterflies, the jugal lobe of the forewing covers a portion of the hind wing.
4. Also, in other insects, margins of the fore and hind wing overlap or the hind wing bristles or frenulum hook up in the forewing.
5. When at rest, wings are held over the back in most insects causing longitudinal or transverse folding of the wing membrane.
6. Normally, there will be radial fold lines to the base of the wing allowing the adjacent wing to be folded over or under each other.
7. In cockroaches and locusts, the anal part of wings is folded like a fan along the veins.

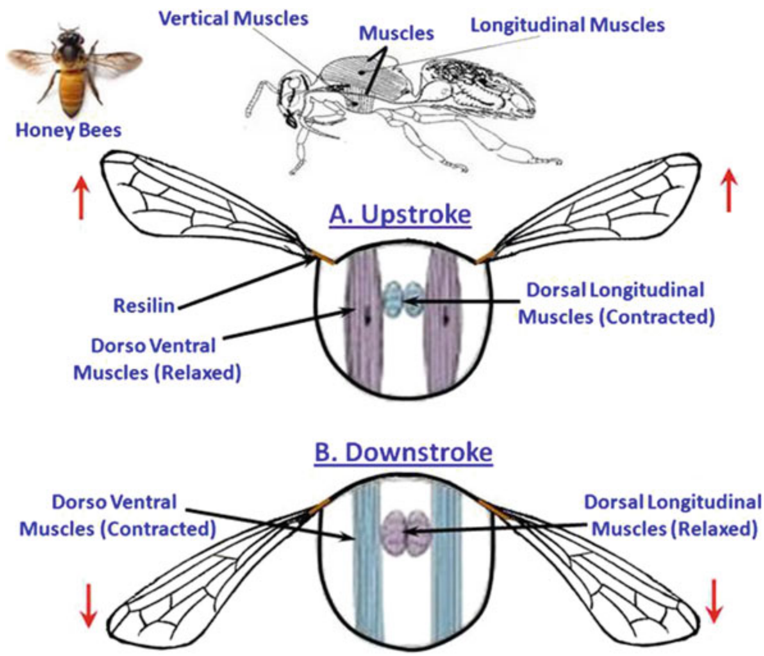

Fig. 4.7 Illustrating the indirect muscle action in an insect

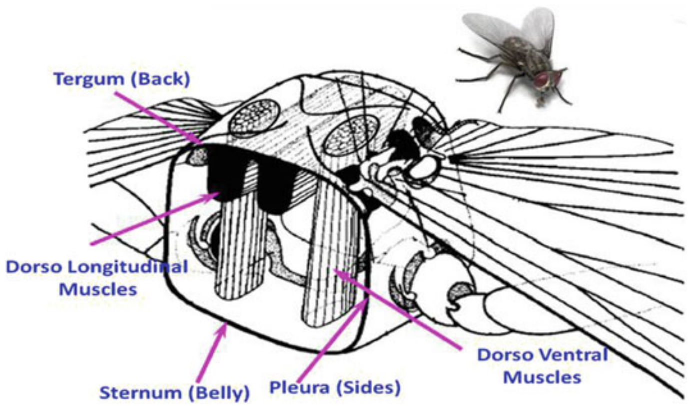

Fig. 4.8 Transverse section of thorax—housefly (Illustrative)

8. Folding of the wing is produced by a muscle arising on pleuron and inserted into the third axillary sclerite of the wing; interestingly, the activity of the same muscle in insect flight affects the power output of the wing. Thus, it is also important in flight control.

9. The wing movements consist of the upstroke, downstroke, flexion and forward and backward movements. Rotational movements along the longitudinal axis of the wing contribute to forming an approximate figure of eight "8" at the wing tip. The downstroke of the wing is brought about due to the elevation of the tergum.
10. The downstroke is also accompanied by a forward movement. The upstroke is associated with the backward movement of the wing.

Flight Parameters

The basic and derived flight parameters of an insect are as follows:
Basic Parameters:

a. Body Mass (M)
b. Wing Length (l)
c. Wingspan (L)
d. Wing area (A)
e. Area of two wings ($2A$)
f. Disc Area (S_d).

Derived Parameters:

a. **Average Breadth of Wing**: Average breadth of the wing is calculated as 2A/2 l. B_{eff} is an important wing characteristic parameter in calculating wing area and wingbeat frequency of the flier. It may be mentioned here that a change in camber through a differential change in the value of B_{eff} will contribute to additional lift in insect flight. B_{eff} is also calculated by the strip analysis method which is also used in the study of Moment of Inertia (MI).
b. **Wing Loading (W_L)**: It is the ratio of body mass to total flight surface area (2A) and is expressed in gm/cm^2.
c. **Disc Loading**: It is the ratio of mass to disc area. It is expressed in gm/cm^2. W_L helps in calculating frequency and other related power calculations. The weight of the flier gets distributed over the flight surface as wing loading during flight. It may be mentioned that the effective wing area will be changing during flapping of the wing due to which the wing loading values also vary.
d. **Aspect Ratio (AR)**: It is the ratio of the square of wingspan (L^2) to total flight surface area (2A). The aspect ratio in insects usually ranges from 3 to 5. The aspect ratio has an important impact on flight performance. Insects having a high aspect ratio can fly more efficiently as compared to those with a low aspect ratio. MAVs designed on flight principle have low AR.
e. **Airfoil (Aerofoil)**: Transverse Section (TS) of the wing is known as the Airfoil section. In insects, TS is very small and airfoils are very thin. The section varies along the wingspan in terms of the chord, thickness distribution and camber. The wing is flexible and hence, the camber can be changed and get altered during different strokes, and hence can modify the aerodynamic forces as well.

f. **Wingspan Loading (WSL)**: It is the ratio of mass to the square of wingspan and is represented as M/L^2. M/L^2 is also a ratio of wing loading to aspect ratio. M/L^2 is an important aerodynamic parameter that helps in the calculation of wingbeat frequency and other related parameters. M/L^2 represents the flight efficiency better than W_L and the aspect ratio is considered separately. Earlier researchers have not realized the significance of the wingspan loading parameters in bio-aerodynamic studies involving flapping wing motion. M/L2 becomes important in comparative aerodynamic studies [1].

Some Useful Definitions

a. **Flight Velocity**: The speed and direction of a flier in the air are known as flight velocity. For insects, it is usually expressed in metres per second (m/s).
b. **Relative Wind (RW)**: The speed and direction of air impinging on a flier are known as relative wind. It may be stated that it is equal and opposite to the direction of the flight path velocity.
c. **Angle of Attack (AOA or α)**: The *acute angle* between the relative wind and the chord line of an airfoil is known as the Angle of Attack. With an increase in AOA, lift also gradually increases until the stalling angle of attack is reached.
d. **Lift (L)**: The component L of the aerodynamic force, which is perpendicular to the relative wind, is known as Lift.
e. **Drag (D)**: The component D of the aerodynamic force, which is parallel to the relative wind, is known as Drag. It may be noted that drag always opposes the flight motion. There are various types of drag acting on fliers such as surface drag, body drag and induced drag at wing tip which is responsible for the formation of wing tip vortices.
f. **Centre of Pressure (CP)**: The point on the chord line where the aerodynamic forces intersect is known as centre of pressure.
g. **Laminar Flow**: Smooth airflow with a little transfer of momentum or energy between parallel layers is known to be laminar flow.
h. **Turbulent Flow**: Flow where streamlines move fast and break up and there is a considerable mixing up of the layers is known as turbulent flow. There will be an exchange of momentum between different layers. Unsteady flows can be an example of turbulent flow.

Wingbeat frequency: It is expressed as the number of wingbeats or oscillations per second (cps/ Hz). The wingbeat frequency may be empirically calculated as follows:

$$\text{Wing beat frequency}(\vartheta_h) = \frac{\text{Mass of the flier}}{(\text{Wing span})^2 \times \text{B}_{\text{eff}}} \times \text{Constant}$$

Table 4.2 Comparision[b] of typical wingbeat frequencies of different insects

S. No	Primitive fliers (Neurogenic-Synchronous)		Advanced fliers (Myogenic-Asynchronous)	
	Type of flier	Wingbeat frequency (cps/Hz)	Type of flier	Wingbeat frequency (cps/Hz)
1	Large butter fly	**10**	Soapnut bug (*T.j*)[a]	**50**
2	Damselfly	**16**	Chrysocoris	**100**
3	Cockroach	**20**	Bumblebee	**130**
4	Locust	**25**	Housefly	**190**
5	Scorpionfly	**28**	Honey bee	**250**
6	Dragonfly	40	Mosquito	600
7	Humming Moth	85	Forcipomia	1000

[a]Low ϑ_h observed in *T.j* due to secondary adaptations since primarily ***T.j*** is a myogenic flier hence the frequency is 50Hz
[b]From various sources

The small insects are observed to have a higher frequency in contrast to bigger fliers. The wingbeat frequencies of some of the fliers given in Table 4.2 are modified after [2] and [1]. The wingbeat frequency of some of the fliers is as follows:

Table 4.3 reads detailed flight parameters measured and calculated for ***Tessaratoma javanica*** (***T.j***) and ***Chrysocoris purpureus*** (***C.p***) for a better understanding and comparison. The parameters selected here also may form the quantitative basis for the experimental design of Insect Mimicking MAVs based on bio-mimicking principles.

Typical forward velocities of some common insects have been shown in Table 4.4.

Based on Table 4.5 of the flight parameters, the derived flight features of the above insects can be understood and calculated which help in understanding the natural flight of these fliers.

Moment of Inertia studies have been carried on insect wings by using the strip analysis method, which may give a general idea of lift, thrust and distribution of mass and area in relation to wing strips as counted from the fulcrum. The study of MI helps in understanding the properties of moving bodies including insects (more details are discussed in Chap. 6). Insect flapping flexible wing is peculiar in the sense that the upper part of the wing develops lift, the lower part thrust because of bending and the tip develops induced drag (tip vortices). It is a thin tapering chitinous membrane supported by longitudinal veins, which make it anisotropic and contribute to the aeroelastic properties of the wing. The bending of the insect wing is a resultant of uneven distribution of mass which decreases from fulcrum to the wing tip.

Table 4.3 Flight parameters of two pentatomid (Heteroptera) insects [1]

Sl. No	Parameters	Notation	Units	*Tessaratoma javanica*	*Chrysocoris purpureus*
1	Mass	M	gm	0.860	0.170
2	Wing length	*l*	cm	2.20	1.20
3	Wing breadth	Beff	cm	1.15	0.65
4	Wingspan	L	cm	6.00	3.16
5	Wing area	2A	cm^2	5.00	1.60
6	Fineness (*l/b*) Ratio		–	2.00	2.00
7	Wing loading	W_L	g/cm^2	0.20	0.11
8	Wingspan loading M/L^2 (WSL = WL/AR)	WSL	g/cm^2	0.03	0.018
9	Aspect ratio	AR	–	6.8	6.3
10	Wingbeat frequency	ϑ_h	cps	50	90
11	Stroke period $\frac{1}{\vartheta_h} x 1000$	T	ms	20–22	10–12
12	Reynolds number	*Re*	–	4000	1000
13	Disc area	–	cm^2	27	8.0
14	Disc loading	–	g/cm^2	0.034	0.021
15	Wing swept area	–	cm^2	9.5	3
16	Velocity	V	m/s	3.5	0.11
17	Weight of two wings	–	gm	17.33×10^{-3}	2.01×10^{-3}
18	Angular velocity	–	rad/sec	325	700
19	Angular acceleration	–	rad/s^2	1.03×10^5	4.5×10^5
20	Angular momentum	–	$g\ cm^2/s$	–	1.12
21	Moment of inertia	MI	$g\ cm^2$	0.03	–

Table 4.4 Typical forward velocity of insects during flight (*from various authors)

Type of flier	Speed in mph
Locust	20.5
Dragonfly	15.6
Humming bird moth	11.1
Bumblebee	6.4
Honey Bee	5.7
Housefly	4.4

Table 4.5 Comparision of[a] Flight Parameters of Various Insects

Parameter	Units	Primitive insects	Advanced insects		
		Dragon fly	*Chalcid wasp*	*C.purpureus*[a]	*T.javanica*[a]
B_{eff} (Chord)	cm	1		0.65	1.15
l	cm	4	0.5 – 0.7	1.2	2.2
L	cm			3.16	6.0
ϑ_h	Hz	40	400	90	50
Forward velocity (V)	m/s			1.8–2	3–4
Re	–	103	25	1000	4000
Mass	gm			0.17	0.86
Angle of attack($\propto$)	deg	25–45	25–45	25–45	25–45

[a]This work is carried out at SNIST, Hyderabad, others from various sources

Insect Flight Muscles

The arrangement of direct and indirect flight muscles in the thorax and their contribution to up and down movements of the wings in both primitive and advanced insects have been discussed. However, the wingbeat frequency is an important parameter that helps in classifying the insects as Neurogenic (Synchronous) and Myogenic (Asynchronous) fliers. The differences between these two types of fliers have been listed below in Table 4.6.

Table 4.6 Differences between neurogenic and myogenic fliers

S. No	Neurogenic fliers (Synchronous)	Myogenic fliers (Asynchronous)
1	Frequency of wingbeat (ϑ_h): 2–200cps	Frequency of wingbeat (ϑ_h): 200–1000cps
2	Primitive insects such as dragonflies, cockroaches and locust	Advanced insects such as houseflies, mosquitoes and drosophila
3	Metabolism of flight muscles—oxidative type	Metabolism of flight muscles—highly oxidative and depends on fat metabolism
4	Number of mitochondria (cristae)—more (++)	Number of mitochondria (cristae)—more (++++)
5	Wing tip mutilation frequency does not increase	Wing tip mutilation frequency increases by 50% or more
6	Resilin elastomer at wingbase is moderately developed	Resilin elastomer at wingbase is more efficiently developed
7	Flight muscle contraction—Twitch-like (Direct muscles)	Flight muscle contraction—Tetanus-like oscillations (Indirect muscles)
8	Sarcoplasmic Reticulum (SR)—Highly developed for storing calcium	Sarcoplasmic Reticulum (SR)—developed for storing calcium
9	Small myofibrils	Large myofibrils

Table 4.7 Energetics of catabolism (Bio-molecules Oxidation)*

Type of biomolicules and metabolic pathway	Number of ATPs produced	Total energy (kJ)
Glucose and glycolysis and TCA cycle	26–38	780–1140
TAG (fatty acid C16)	129 + 16	4350
Proline (Oxidative Deamination, TCA)	15	450

*ATP upon hydrolysis yields 7.3 k cal/mol or 30.5 kJ/mol
*Insect spends 57 J of energy/gram body weight/hour of flight

Myofibrils are made up of fine actin filaments (I-band) and thick myosin (A-band) filaments. Actin filaments are isotropic and myosin filaments are anisotropic. Troponin and tropomyosin proteins block the myosin head from coming in contact with actin. Due to nerve impulse action, the calcium is released from the SR and this in turn removes the TN-TM blocking. In the presence of ATP, the ATP hydrolysis takes place leading to muscle contraction. Regulation of oscillatory contraction in flight muscle by troponin is rather well known. The sarcomere is the basic unit of muscle contraction within the sarcomere, with the arrival of a nerve impulse at Motor-end-plates (MEP), I-filaments slide against free ends of A-filaments leading to muscle contraction. Flight muscles shorten by about 1%. The asynchronous flight muscles produce remarkable amounts of tension in muscle fibres, in the presence of large amounts of free calcium available in the cytoplasm in contrast to synchronous muscles.

Insect flight muscles are metabolically highly active such as they have more of oxidative enzymes, mitochondrial respiration and aerobic capacity. Insect flight muscles depend on trehalose, proline and lipids as fuels in the metabolism. Carbohydrates like trehalose and proteins like proline are used during short flights. After carbohydrates, amino acids also provide a major source of energy in many insect flight muscles. Fatty acids are the fuels for long-duration and long-distance flight. Locusts, hawk moths and beetles depend on fatty oxidation. Fats are stored as triglycerides and they are released as diglycerides. Fat produced double the energy as compared to the unit weight of carbohydrate.

Since this book is dealing with the bio-aerodynamics of insect flight, instead of going into the details of metabolic pathways such as Glycolysis and Citric acid cycle, the energetics of these pathways are given the form of Table 4.7.

Summary

The structure of the thorax including the flying segments (pterothorax) and associated wings and their morphology have been considered in detail. Wing venation, which forms the supporting structural basis for the wing and its significance in the classification of insect orders, has been elucidated. The wing is attached to the thorax by a membranous basal area having sclerites, also known as pteralia, which along with their attached muscles help in flapping and rotation. Direct and indirect muscles have been described in detail, which help in wing movements.

Flight parameters of body and wing contribute to the basic understanding of insect flight and its novelty. Some aerodynamics terms have been defined clearly for the sake of convenience and clarity. Wingbeat frequencies of insects, forward velocity and flight parameters have been summarized. It has to be emphasized that flight parameters of two pentatomid bugs such as ***Tessaratoma javanica*** and ***Chro purpureus*** have been studied in all the possible details so that this may possibly help and inspire for the design of bio-mimicking MAVs [1].

Differences between neurogenic and myogenic fliers, the basis of muscle contraction and energetics have been explained briefly. Oxidation of bio-molecules has been briefly summarized in the form of a (Table 4.7).

Insect flight muscle and cardiac muscle appear to contract rhythmically but differently. The Ca^{2+} sensitivity of cardiac and flight muscle (water bug, Lethocerus) can be manipulated experimentally. The cardiac and flight muscle have thick and thin filaments adapted for oscillatory mechanical movements (Belinda Bullard and Analisa Pastore, JA Muscle Res. Cell Motil, 2019). This has been further supported by recent research articles (2021).

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Chapter 5
Types of Textures in Insect Wings and Classification

N. Chari, A. P. Rao, Ponna Srinivas, and N. Girish

Abstract Classification of flying insects into orders is based on the structure of chitinous membranous wings, which are membranous outgrowths of the exoskeleton. Distinct wing morphology and their design is characteristic feature of many orders (25). Wing texture is highly characteristic for each ptereygote insect order and is highly variable.

Keywords Peterygota · Wing structure · Fringed wings · Elytra · Halters · Wing venation · Scutellum

Introduction

Butterflies and moths are classified as Lepidoptera, a word that literally means wings having scales. Beetles belong to Coleoptera having hard elytra. The forewings of beetles, which are hard, chitinous structures, protect the membranous delicate hind-wings and are known as elytra. Bees and wasps are Hymenoptera because of their membrane-textured wings. Flies possess only mesothoracic functional wings and are named as Diptera and metathoracic wings (Halters) are rudimentary and act as balancers. Wings of insects will help to escape from enemies, to find food and mates and in migration. Wings are the characteristic features of adult insects and their texture helps in coloration, survival, mimicking, protection to a large extent and in classification.

Wings are the membranous outgrowths of insect exoskeleton that allow insects to fly. They are found on the meso-thorax and meta-thorax (second and third thoracic segments). These two pairs of wings are often referred to as the fore and hindwings, respectively. In apterygote insects, the wings are absent. It is quite probable that the

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primitive winged insects had no wing folding mechanisms in contrast to modern advanced insects and they used to glide in the air.

The wing membranes are supported by a number of longitudinal veins, which also have cross-connections that form closed "cells" in the membrane. The patterns resulting from the fusion and cross-connection of the wing veins are often diagnostic features for different evolutionary lineages and can be used in the classification and identification of the family or even at the genus level in many orders of insects. The wing venation is subjected to variations in various orders; however, it appears characteristic for each order for taxonomy.

The wings may be present only in one sex as in male; rarely, female (as in figwasps) and in some velvet ants. They are selectively lost in "workers" of social insects such as ants and termites. In some cases, wings are present only at a particular part of the life cycle. The structure and colouration of the wing will often vary. At rest, the wings may be flat or folded on the abdomen, where the forewings cover the folded hindwings. In foraging insects like bees, wings withstand wear and tear. In beetles and bugs, the second pair of wings have resilinous patches contributing to wing deformations and efficiency of flight.

The evolution of insect wings is not well understood. The four main theories for the evolution of wings are as follows:

1. Wings are developed from paranotal lobes such as extensions of the thoracic integument from the pleuron.
2. They are modifications of movable abdominal gills as found in aquatic naiads (nymphs) of mayflies.
3. Insect wings arose from the fusion of pre-existing endites and exites of crustaceans.
4. Insects have long been separated from other vertebrate fliers phylogenetically, morphologically and structurally. However, their wings develop similar aerodynamic adaptation forces for flight. This is a very good example of analogous structures developing homologous aerodynamic forces during a prolonged course of evolution.

Distinct wing morphology (design) is a characteristic feature of many insect orders. Wing textures in different orders of insects are discussed in the following sections. Wing texture has been explained to understand their ecological adaptability and aerodynamic requirements in different types of flight.

Orthoptera

The forewings of grasshopper are elliptical leathery or parchment-like opaque **tegmina** and are narrow (Fig. 5.1). Like the elytra of beetles and the hemelytra of plant bugs, the tegmina help to protect the delicate hindwings. The hindwings are broad, membranous and folded in a fan-like manner. Locusts are known for their long-distance migration covering 5000 kms on their wings. The wing design must be

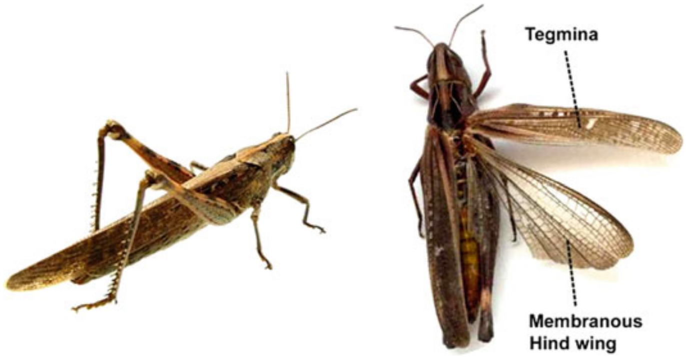


Fig. 5.1 Features of orthoptera

unique for an insect weighing about 2 gm for covering such a long distance during migration.

Examples: Locust, Grasshoppers and Crickets.

Blatteria

The body is oval and dorso-ventrally flattened. The head is usually covered by prothoracic pronotum, and they are dull in colour and poor fliers. Some insects are apterous. Males are good fliers as compared to female cockroaches (Fig. 5.2). Their wingbeat frequency is below twenty. The Madagascar hissing cockroach has no wings.

Examples: Roaches and Cockroaches.

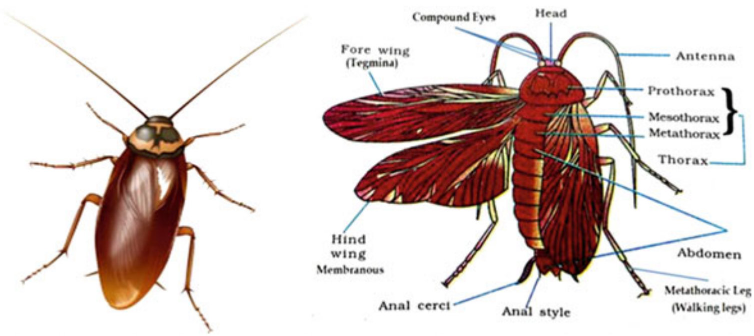


Fig. 5.2 Dorsal view of a cockroach

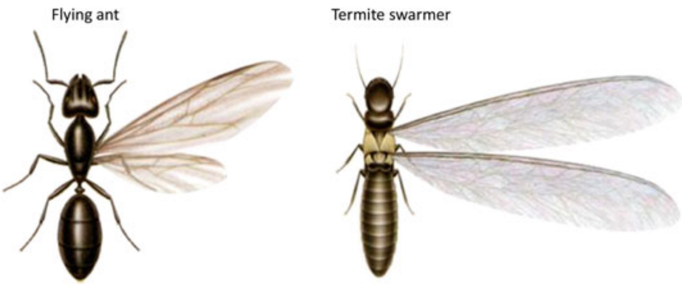


Fig. 5.3 Termites

Isoptera

These are social insects living in large colonies. They are small to medium sized, pale coloured social insects living underground. In macropterous forms, two pairs of wings are present which are similar in size, shape and venation (Fig. 5.3). Venation is simple with few cross-veins. Wings are shedding type. Wings are present only in Macropterous forms. Termites are poor fliers and live inside the wood and soil (subterranean). Termite mounds are known in India and Africa. The life history of termites is highly complicated.

Examples: Termites and White Ants.

Ephemeroptera

The wings are **membranous**, delicate with extensive venation and are held upright like those of a butterfly (Fig. 5.4). The wings have many veins and cross-veins. Forewings are large and triangular. Hindwings are smaller and fan-shaped. The second segment of the thorax, which bears the forewings, is enlarged for accommodating the main flight muscles. Simple and hemi-metabolous type of metamorphosis is found in mayflies and they have a very short life.

Fig. 5.4 Mayfly

Fig. 5.5 Dragonfly—ventral view

Example: Mayfly.

Odonata

Dragonflies and damselflies have two pairs of long wings that are almost equal in size and shape. **Membranous wings** are thin, long and more or less semi-transparent (Fig. 5.5). Wings are supported by a system of tubular veins. The wing veins are fused at their bases and the wings cannot be folded over the body. The main veins and the cross-veins form the wing venation pattern. There may be very numerous cross-veins or very few and the wing venation patterns differ. Usually, the abdomen is very long, and Nymphs or naiads are aquatic.

Examples: Dragonflies and Damselflies.

Dragonfly is a four-winged primitive flier. Wings twist and turn fast. The flier has a low neurogenic frequency of 30–40 Hz. Dragonflies have a long distinct abdomen. They are common good fliers. Metamorphosis is relatively simple (Hemi-metabolous).

Thysanoptera

Thrips are tiny, slender insects having strap-like forewings and hindwings with long fringes of hair, called **fringed wings** (Fig. 5.6). Wing lamina is usually reduced in size with long hair or spine veins are absent. These insects literally swim through the air as though it is a viscous medium. It is a serious agricultural pest. Metamorphosis is simple. Thripidae is the largest injurious family for agricultural crops.

Example: Thrips.

Fig. 5.6 Thrips

Fig. 5.7 Soapnut bug (*T. Javanica*)

Hemiptera (Heteroptera)

The forewings of Hemipterans are said to be hemelytrous because they are hardened (thick and leathery) throughout the proximal two-thirds, while the distal portion is membranous. The second pair of wings are thin and membranous (Fig. 5.7). Unlike elytra, hemelytra function primarily as flight wings contributing to frequency flight. The hemelytra are linked in flight to the hindwings and remain aerodynamically functional as in *T. javanica.* In many plant bugs, Tergum is large and covers the abdomen partially as scutellum. The upper part of the forewing is hemelytra-like and is coupled to a membranous hindwing. The two wings act as one unit on each side during flight. They are moderate fliers, and wings are highly flexible, undergo elastic deformation and contribute to aerodynamic forces. The hindwings are highly membranous and have small patches of resilin as in some beetles.

Example: Soapnut Bugs.

Homoptera

It has a group of a large number of species in these orders. "Heteroptera" is a Greek term for "different wings" while in Homoptera, wings are entirely membranous as in *Cicada.* Interestingly, they do not fly long distances. Cicada is an ideal

Fig. 5.8 Cicada

homopteran insect that comes under the category of Flapping Wing Micro Aerial Vehicle (FWMAV) type. Cicada is an ideal insect for design because of its large weight to sing size ratio, adapted for speed variations (Fig. 5.8).

Example: Cicada.

Lepidoptera

In butterflies and moths, the forewings and hindwings are covered with overlapping scales or hair (Fig. 5.9). The scales are unicellular, flattened outgrowths of the body wall. Most scales are lamellar, or blade-like, and attached with a pedicel. The other forms may be hair-like or specialized and may act as secondary sexual characteristics. Scales are responsible for colour due to the pigment contained within their lamellae. The scales are important in smoothening the airflow over wings and body

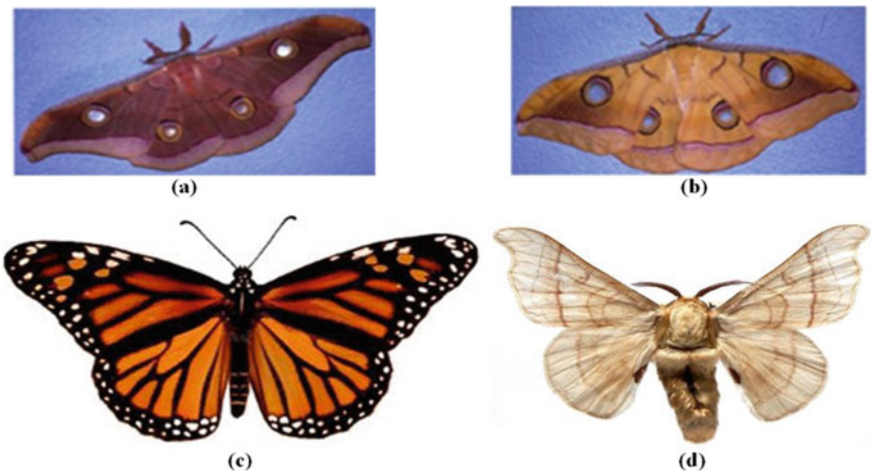


Fig. 5.9 Tasar moth. **a** Male, **b** female, **c** dorsal view of monarch butterfly, **d** dorsal view of ***Bombyx*** Moth

and thus reduce drag during flight. They also insulate the insect against cold. Scales and their colour also help in camouflage, mimicry and in seeking mates. In many small butterflies, the flight is of zig-zag type and thus helps in attaining high lift in a gradual fashion. Some moths are nocturnal fliers and hence highly specialized. Metamorphosis is complete. Two pairs of large wings are present. Some moths are known for echolocation and for escaping from predatory bats during flight.

Examples: Butterflies, moths, silk moths and Monarch butterfly.

Coleoptera

In most species of beetles, the forewings are heavily sclerotized (hardened) and thick and are known as elytra (singular elytron). In Coleoptera, the forewings act as parachuting devices and contribute to lift. The hindwings are membranous, resilient and longer than the elytra, folded longitudinally and transversely under the elytra, which protect the delicate hindwings when at rest (Fig. 5.10a). The elytra tend to cover the hind part of the body and protect the delicate hindwings. The elytra are connected to the pterothorax. The elytra must be raised and maintained in a horizontal position in order to move the hindwings and maintain lift during flight.

A beetle's flight wings are crossed with veins and are folded after landing and are covered below the elytra (Fig. 5.10b). In some ground beetles and in weevils, the ability to fly has been lost secondarily, and hence, they have the two elytra fused together, forming a shield over the delicate abdomen. The wings are rotated forward on their base into flight position. This action spreads the wings as they unfold their wings horizontally. There is a spring mechanism in the wing structure. The wing venation is reduced and modified due to its folded nature. In glow-worms, both the

Fig. 5.10 **a** Elytra spread out and **b** Elytra closing the abdomen

ability to fly and protection from the elytra have been lost (Lampyridae). The light varies from yellow, orange and green to red. Metamorphosis is complex.

Example: Beetles, Jewel Beetles and Weevils.

Hymenoptera

Both the forewings and hindwings are thin and transparent (**membranous**) (Figs. 5.11 and 5.12). The forewings are much larger than hindwings. Both the wings are supported by a system of tubular veins. They are useful in flight. The forward margin of the hindwing has a number of hooked bristles, or "**hamuli**", which lock onto the forewing, holding them together. The smaller species tend to have only 2–3 hamuli on each side, but the largest wasps may have many, which keep the wings gripped together tightly during flight. Hymenopteran wings have relatively few veins compared to many other insects. There is a prominent stigma or pterostigma in the forewings of many species. Because of foraging habits, wings can withstand wear and tear and can repair costal break. This has the aerodynamic advantage for a forager exposed to vegetation and flowers. The abdomen is quite distinct. Many groups have social organizations.

Examples: Bees, Bumble Bees, Ants, Wasps and Ichneumonid.

Fig. 5.11 Honey bee and wasp

Fig. 5.12 Wasp an ichneumonid

Fig. 5.13 Housefly and mosquito

Diptera

In houseflies and mosquitoes, forewings are the only functional pair of wings used in flight. These are thin and more or less transparent membranous wings. Hindwings are modified into small knobbed vibrating organs called halters, which help the insect to sense its orientation and movement, as well as act as balancing organs and provide the needed stability during flight (Fig. 5.13). Halters vibrate out of phase with the wings. Perturbations due to rotations are picked up by tiny hairs near the halters to give a simple effect of a gyro. Many dipteran fliers have a high wingbeat frequency. Some mosquitoes flap their wings 1000 times per second. Flies are among the fast fliers with high wingbeat frequency, increasing with mutilation.

Examples: Houseflies, Mosquitoes and Syrphid Flies.

Neuroptera

It consists of two pairs of wings. Normally, two pairs of wings similar in size, shape and venation are variable. Many longitudinal and cross-veins are present (Fig. 5.14). Venation has a network of veins. They are poor and erratic fliers.

Examples: Nerve Winged Insects or Lacewings.

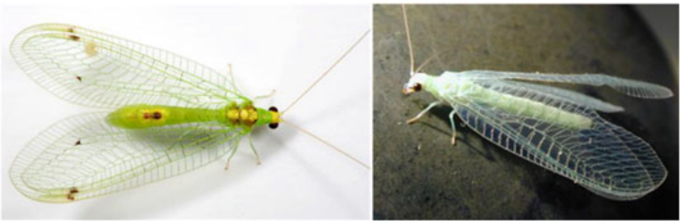


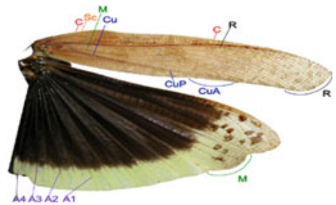
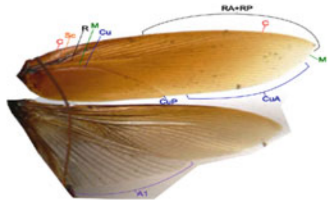
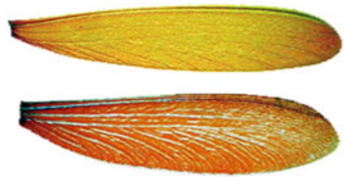
Fig. 5.14 Lacewings

Summary

Class Insecta (Hexapoda) is divided into two subclasses Apterygota and Pterygota. Apterygota consists of primitive insects having six legs and no flying wings like Protura, Thysanura and Collembola. Subclass Pterygota has 28 flying insect orders and only a few orders have been quoted in the present study, which are of consequence in bio-aerodynamic studies. The names of orders, wings details and their examples are shown in Table 5.1.

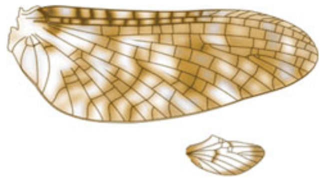
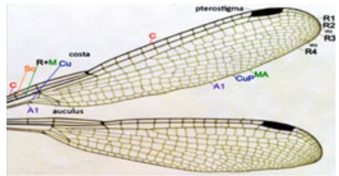
The detailed classification of the insects is beyond the scope of this book (Table 5.2).

Table 5.1 Classification (Nomenclature) of insect orders based on morpho-functional properties of wings (from various sources)

S. No	Orders	Wing details	Examples	Remarks	Wings
1	Orthoptera	Two pairs of wings First pair leathery (Tegmina) Second pair membranous and well developed. Both linked in flight	Locust, Grasshoppers and Crickets	Hindwings fold in fan-like fashion. ν_h is 20–25 Hz	
2	Blattaria	Large-sized Insects with flying wings. Body flattened. Some of them have no wings. The forewings are leathery and the hindwings are membranous. They are poor fliers. Wings with netted venation	Roaches and cockroaches	Poor fliers, males are active	
3	Isoptera	Two pairs of wings. Both are similar in size and shape. Flight for a short duration Venation simple with cross-veins Wings are shedding type and sometimes they are absent	Termites and White Ants (Social Insects)	Relatively poor fliers	

(continued)

Table 5.1 (continued)

S. No	Orders	Wing details	Examples	Remarks	Wings
4	Ephemeroptera	Two pairs of multi-veined, delicate wings held on the top of the back. The second pair greatly reduced or absent. Wings are held vertically over the back	Mayflies in large groups are day fliers	Short lived (one day)—but few hours	
5	Odonata	Two pairs of long narrow new veined wings. Held straight from the wings' vestigial sides. The abdomen is long and slender. Unequal wings	Dragonfly, Damselfly (Wings not coupled)	Each wing moves independent of each other. ν_h is 30–40 Hz	
6	Thysanoptera	Fringed wings small insects. Both wings are slender	Thrips	Flight is similar to "swim in air", not good fliers	

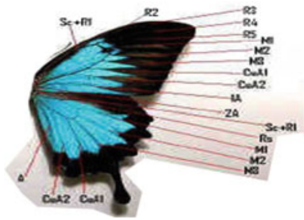
(continued)

Table 5.1 (continued)

S. No	Orders	Wing details	Examples	Remarks	Wings
7	Heteroptera (Hemiptera)	Two pairs of wings (hemelytra). First pair partially elytra and the rest membranous. Second pair membranous and attached to first pair and scutellum well developed as a shield and has aerodynamic importance	Plant bugs, animal bugs, Belostoma (a water bug) and soapnut bug. Lithocerus (10 cm) is the largest bug	ν_h is 50–100 Hz	
8	Homoptera	Two pairs of wings. Wing venation is prominent with stiff wings, both of equal size. Stridulatory and auditory organs are present in Cicada	Cicada, Leaf Hoppers and Aphids	Low-frequency fliers. Cicada is ideal for Biomimicking designs	

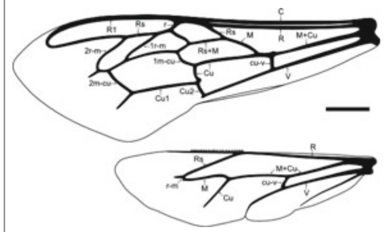
(continued)

Table 5.1 (continued)

S. No	Orders	Wing details	Examples	Remarks	Wings
9	Lepidoptera	Two pairs of wings that overlap during flight, rarely vestigial. They are covered with scales. Forewings are larger than hindwings and have many branched longitudinal veins	Butterflies and Sphingid moths	Flight is zig-zag. Wings are covered by scales. Good fliers. ν_h is 2–10 Hz	
10	Coleoptera	Two pairs of wings, the first pair is hard, known as elytra which do contribute to lift. Sometimes, two elytra are completely fused on the abdomen. The second pair is membranous and contributes to thrust. It has few veins	Beetles, jewel beetles and Weevils	ν_h is 50 Hz approximately	

(continued)

Table 5.1 (continued)

S. No	Orders	Wing details	Examples	Remarks	Wings
11	Hymenoptera	Two pairs of thin membranous wings. The second pair is small. Venation may be reduced and stigma is present	Bumblebees, Honey bees, Wasps and Ants (Social insects)	ν_h is above 100 Hz	
12	Diptera	Two pairs of wings, only forewings are functional. Second pair acts as halters (balancers and gyroscopic action). Halters are regarded as vestigial organs (small)	House flies, mosquitoes	ν_h is 200–1000 cps	

(continued)

Table 5.1 (continued)

S. No	Orders	Wing details	Examples	Remarks	Wings
13	Neuroptera	Two pairs of wings, normally similar in size. Venation is variable. May be longitudinal and cross-veins present (veined wings). They are poor and erratic fliers	Nerve-winged insects. Lacewings	Poor fliers	

[a]For detailed classification, the reader may refer [1]

Table 5.2 Classification of insects

Subclass	Orders	Examples
I. Aterygota (primitive wingless insects)		
	1. Protura	Telsonatails (***Acerentomon, Acerentulus***)
	2. Collembolan (glue)	Springtails (***Sminthurus, orchesella, Isotoma***)
	3. Thysanura (tassel tail)	Silverfish (***Lepisma***)
II. Pterygota (winged insects)		
Division-1. Exopterygota (Heterometabola) insects with simple metamorphosis	4. Ephemeroptera	Mayflies (***Ephemera***)
	5. Placopterida (folded wings)	Stoneflies (***Isoperla***)
	6. Odonata (toothed)	Dragonflies, Damselflies
	7. Embioptera (straight wings)	Webspinners (***Oligotoma***)
	8. Orthoptera (straight wings)	Grasshopper, Locust
	9. Phasmida	Leaf insect, Stick insect
	10. Dermoptera (skin wings)	Earwig (***Forficula***)
	11. Blattaria	Cockroaches
	12. Mantoidea	Praying mantids
	13. Isoptera (equal wings)	Termites, white ants
	14. Corrodentia/Psocoptera (gnawing)	Booklice (***Liposcelis***)
	15. Mallophaga	Bird lice, biting lice
	16. Anoplura/Siphunculata (unarmed tail)	True lice, sucking lice (***Pediculus***)
	17. Thysanoptera (tassel wing)	Thrips (***Heliothrips***)
	18. Heteroptera	True bugs, Soapnut bug
	19. Homoptera (half wings)	Cicadas, Aphids, Scale insects (***Cimex, Belostoma***)
Division-2. Endopterygota (Holometabolous) insects with complete metamorphosis	20. Coleoptera (sheath wings)	Beetles
	21. Hymenoptera (membrane wings)	Ants, Bees, Wasps
	22. Megaloptera	Dobson flies
	23. Neuroptera (nerve wings)	Lacewings
	24. Mecoptera (length wings)	Scorpion flies (***Panorpa***)

(continued)

Table 5.2 (continued)

Subclass	Orders	Examples
	25. Trichoptera (hair wings)	Caddisflies (***Platycentropus***)
	26. Lepidoptera (scale wings)	Butterflies, Moths
	27. Diptera (two wings)	Gnats, Mosquitoes, Houseflies
	28. Siphonaptera/Aphaniptera	Fleas (***Pulex, Senopsylla***)

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Chapter 6
Theories on Hovering Flight of Insects

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Abstract Seven classical theories have been suggested for calculating wingbeat frequency in hovering state of flight. In Mass flow theory of Hovering, frequency is calculated based on the rate of mass flow of air; and insect is in dynamic equilibrium. This was suggested by Puranik et al. The value of K is variable in different theories. In Mechanical oscillatory theory, the oscillating wing is considered as a mechanical oscillator. Wing length is in millimetres and K is 3540. This theory was suggested by Greenwalt. Crawford's theory is a modified Mass flow theory where wing swept area replaces wingspan square and stroke angle is small. This is applicable for small insects. Norberg's theory is based mainly on the mass of the flier (and other flight parameters) which is related to power of the flier. Pennycuick's theory is based on multiple regression and dimensional analysis. Theory based on Newton's Law is on mass flow concept. Deakin's theory, he applied dimensional analysis concept. This is particularly applicable to insect hovering.

Keywords Disc area concept · Harmonic oscillator · Wing swept area · Wingspan loading (WSL) · Dynamic equilibrium

Introduction

The hovering flight requires normally more power than does the forward flight. However, the discrepancy may become less significant for the insects which weigh far less as compared to birds and bats. Understanding a detailed study of flying insects that seem to hover effortlessly helps in the development of flapping flexible wings for winged nano-scaled MAVs useful for surveillance over small areas. Forward speed being zero in hovering flight, the lift has to be sufficient to balance the total weight

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Table 6.1 Seven classical theories

1	Mechanical oscillator theory	[1]
2	Crawfords theory	[2]
3	Norberg's theory	[3, 4]
4	Pennycuick theory	[6]
5	Theory based on Newton's laws	–
6	Mass flow theory	Puranik and Ahmed [7]
7	Deakin's theory based on dimensional analysis	[12]

of the flier. The buoyant nature of the air also would help in keeping afloat the tiny insects in the hovering state. Birds like certain hawks, kingfishers and hummingbirds also hover for survey and feeding. Hummingbirds are the masters of hovering flight in nature. Among the insects, the hovering flight is found in honey bees, bumblebees, moths, butterflies, some plant bugs and moths during sucking of juice from the plant or nectar from the flowers. In normal hovering, the wing moves in a horizontal plane. Seven classical theories have been mentioned below to predict the hovering capabilities of the various fliers in terms of frequency (Table 6.1).

Out of these seven theories, we are discussing Mass Flow Theory and its related formulae in greater detail because it forms the basis for the interpretation of other theories. Murthy [8] in his Ph.D. Thesis has discussed hovering parameters and hovering of *Carpenter Bee*.

Mass Flow Theory of Hovering

Puranik and Ahmed [7] suggested a theory for wingbeat frequency of a flier on the basis of mass flow of air displaced by wings.

During the hovering state, the reaction force of a flier is proportional to its weight. According to mass flow theory, during the hovering state, the insect is in dynamic equilibrium and the reacting force is proportional to the rate of mass flow of air where

$$R = W \tag{6.1}$$

where,

$$W = M_{f.}g$$

$$\therefore R = M_{f.}g \tag{6.2}$$

$$R\alpha \frac{dm}{dt}$$

where,

R is reacting force of the flier.
$\frac{dm}{dt}$ is the rate of mass flow of air passing over the wings.
M_f is the mass of the flier and
g is the acceleration due to gravity.

The rate of mass flow of air during flight is considered as a function of disc area (S_d), effective wing breadth (B_{eff}), the density of air ρ and wingbeat frequency of flier (ϑ_h).

$$\frac{dm}{dt} \alpha \, S_d B_{eff} \rho \frac{\vartheta_h}{2} \tag{6.3}$$

The wingbeat cycle consists of an upstroke followed by a downstroke. In a flapping cycle, as the downstroke of the wing is considered to be more powerful and contributes to maximum lift than upstroke (recovery stroke), half of the value of wingbeat frequency $\left(\frac{\vartheta_h}{2}\right)$ is included in the above equation as it is derived on an empirical basis. The frequency arrived at the above equation agrees well with experimental observations.

$$R \, \alpha \frac{dm}{dt}$$

$$R \, \alpha \, S_d B_{eff} \rho \frac{\vartheta_h}{2} \tag{6.4}$$

or

$$R = k S_d B_{eff} \rho \frac{\vartheta_h}{2} \tag{6.5}$$

From Eqs. 6.2 and 6.5, we get

$$M_f g \; = k S_d B_{eff} \rho \frac{\vartheta_h}{2} \tag{6.6}$$

where

$$S_d = \pi r^2 = \frac{\pi L^2}{4},$$

and L = wingspan

$$M_f g \; = k \frac{\pi L^2}{4} B_{eff} \rho \frac{\vartheta_h}{2}$$

Rewriting this equation, we get

$$\vartheta_h = \frac{8M_f g}{k\pi \rho L^2 B_{eff}} \tag{6.7}$$

By rearranging the above equation carefully and substituting K' as below,

$$K' = \frac{8g}{K\pi\rho}$$

Hence,

$$\vartheta_h = \frac{8g}{k\pi\rho} x \frac{M_f}{L^2 B_{eff}}$$

or

$$\vartheta_h = K' x \frac{M_f}{L^2 B_{eff}} \tag{6.8}$$

The value of K' is obtained from the slope of the log graph drawn between M_f and $\vartheta_h L^2 B_{eff}$ assuming the density of air corresponds to standard sea levels conditions taken in CGS units. The value of K', thus, obtained is 2086. The above equation of wingbeat frequency is re-interpreted by [9] and [10] in their theses and by Chari et al. (2014).

$$\frac{M_f}{L^2} = WSL = wing\,span\,loading$$

$$M_f = M = Mass\ of\ the\ flier$$

$$\vartheta_h = WSL\,x\,K'\,x\frac{1}{B_{eff}} \tag{6.9}$$

The wingspan loading can also be interpreted as the ratio of wingloading to the aspect ratio of the wing.

$$WSL = \frac{WL}{AR} = \frac{(M/A)}{\left(L^2/A\right)}$$

where WL is wingloading ratio and AR is aspect ratio values, respectively.

On re-substituting for *WSL* value in Eq. 6.9, we get

$$\vartheta_h = \frac{M}{A} x \frac{A}{L^2} x\,K'\,x\,\frac{1}{B_{eff}}$$

or

$$\vartheta_h = \frac{M}{L^2}\frac{1}{B_{eff}}K^{'} \tag{6.10}$$

$$\therefore\ \vartheta_h = f\left(WSL,\ B_{eff}\right) \tag{6.11}$$

Mechanical Oscillator Theory

Greenewalt [1] considered the oscillating wing of a biological flier as a driven mechanical harmonic oscillator and suggested the following equation as

$$\vartheta.\,l^n = K\ \text{(constant)} \tag{6.12}$$

with a value of **3540** for the constant **K** and l is being the wing length in mm. Accordingly,

$$\vartheta.l^{(1\ to\ 1.25)} = 3540 \tag{6.13}$$

The value of n has to be varied between 1 and 1.25 for tallying with the natural frequency of the flier by the trial-and-error method. The value of the wing length (l) has to be expressed in millimetres. Greenewalt confined his experiments to small hummingbirds. This is a very cumbersome method that involves many trial-and-error calculations by changing the power values of the index of l. Therefore, when we apply this formula for the calculation of frequency in biological fliers, it is a long drawn process. Hence, this theory is not generally used for calculating the insect wingbeat frequency.

Crawford's Theory

Crawford [2] proposed modified mass flow theory and obtained a relationship for the wingbeat frequency of small fliers and the equation is as follows:

$$\vartheta_h = \left(\frac{g}{4\pi\rho}\right)^{1/2} x\,\frac{\sqrt{M_f}}{S_w} \tag{6.14}$$

where

M_f Mass of the flier.
S_w Wing swept area = Stroke angle (radians) × (wing length, mm)^2.
ρ Density of air 0.001225 gm/ cm^3 (for standard air at mean sea level).
g Acceleration due to gravity = 981 cm/ s^2.

This theory is applicable where the wing swept area and mass of the insect are relatively small as in the case of a mosquito and other very small insects with a high wingbeat frequency. The value of K as calculated is 252.44.

Norberg's Theory

Norberg [3] suggested the formula for the calculation of wingbeat frequency based on the mass of the flier (M).

$$\vartheta_h = 3.98\ M^{-0.27} \tag{6.15}$$

This formula is applicable to fliers having medium speed and size. However, it is not applicable to hummingbirds which are of specialized category; he proposed a different formula as given below

$$\vartheta_h = 1.32 M^{-0.60} \tag{6.16}$$

Norberg has considered the mass of the flier alone as a criterion for the calculation of wingbeat frequency and assumed that other parameters (flight) are related to it.

Pennycuick's Theory

Pennycuick [5, 6] considered the following parameters to be influencing the wingbeat frequency and suggested the final equation as follows:

$$\vartheta_h = 1.08\left(m^{3/8} g^{1/2} b^{-23/24} S^{-1/4} \rho^{3/8}\right) \tag{6.17}$$

As Pennycuick studied marine birds alone, therefore, the value of K is obtained to be 253 as suggested by him. The density of air is 1.225×10^{-3} gm/cm^3. The universal application of this formula to insects remains to be established by further studies.

Theory Based on Newton's Laws

The hovering frequency formula suggested based on Newton's theory is as follows:

The hovering frequency ϑ_h can be expressed as

$$\vartheta_h = \frac{K\sqrt{m}}{A} \tag{6.18}$$

where

$$K = \frac{1}{2}\sqrt{\frac{981x1000}{4x3.1416x1.125}} = 263.4$$

Hence, the value of K is 263.4.

Newton's formula is basically based on the mass flow concept. However, larger samples of fliers have to be tested by using for generalization of this formula.

Deakin's Theory

Deakin [12] has suggested the following formula for the calculation of wingbeat frequency of insects.

$$\vartheta_h = \frac{317\sqrt{m}}{s} \tag{6.19}$$

where s is the combined area of the two wings. This theory is applicable to a large number of insects. Hence, this can be universal in its application to insect frequency calculations.

The above seven theories and their formulae have been briefly mentioned from Bio-Aerodynamics of Avian Flight [11].

Earlier Work on Hovering

Ellington [13] studied the kinematic changes with the flight speed of bumblebee. Other insects like *fruitfly* and *hawk moth* were also studied. He derived the mass 'm' that can be supported during hovering as

$$m = \frac{0.387\varphi^2 n^2 R^4 C_L}{AR} \tag{6.20}$$

where

φ is wingbeat amplitude (peak to peak in radians).
AR is the aspect ratio of the wing.
m is mass of insect (kg).
n is strokes/seconds of wingbeat, (Hz).
R is wing length (m).

Summary

Symmetrical hovering is found in hummingbirds and insects. This can be summarized as follows:

1. Body mass is usually small and the position of the orientation of the body may be more or less vertical during hovering.
2. Wings move forward and backward coupled with some kind of small rotation at the base.
3. Differential lift is produced during downstroke and upstroke; however, the lift produced during downstroke is about an average value of 65%.
4. Wings are rotated about the wing base during pronation and supination.
5. Hovering is mainly sustained by the wingbeat frequency of the flier.
6. The wing tip traces approximately a figure of ‘8’.
7. The wing is relatively rigid and cambered and the wingspan does not change during hovering.
8. The hovering frequency is relatively high and the variation has a frequency range depending on whether it is a neurogenic or myogenic flier.
9. Hovering is a costly mode of flight in terms of energy consumption.
10. All the seven theories of hovering flight relevant to the insects have been discussed in detail.
11. In hovering, most of the lift is produced during the downstroke and so also the drag.

The wingbeat frequencies of different insects as calculated from above-mentioned theories, particularly from mass flow theory, have been shown in Table 3.1. The experimental and theoretical values as calculated are in good agreement.

In conclusion, for the wing design of an Insect Mimicking MAV, the structure of a hovering insect flier appears to be a more ideal choice. Since it is made up of chitin and has elastomere resilin at the main base. The chitinous thin wing membrane of insects is traversed by a large number of longitudinal veins which contributes to the elastic property of the wing. Aeroelasticity plays an important role in the design and kinematic study of the wing motion since it involves axial stretching, buckling and damped vibrations.

Non-uniform flexibility and structural deformation of the wing in hovering are an important factor which need further study.

Addendum

Salient features of comparison of symmetrical and hovering insects and birds.

- Seen in hummingbirds and insects.
- Size/body mass (5–40 gr) is small and Hovering may be vertical.
- Wings move forward and backward and rotate at the base.
- Differential lift is produced during downstroke and upstroke.
- Wings are rotated at the fulcrum, during pronation and supination.
- Hovering is due to wingbeat frequency.

- Figure of '8' is formed in the vertical plane by the flapping flexible wing at the tip.
- The wing is rigid and cambered and has no flexion except at the tip.
- Example: Cicada and Hummingbird.
- Lift produced in insects during downstroke is 50% and upstroke is about 40%. In
- hummingbirds downstroke is 70% and in upstroke is 30%.
- The hovering frequency is high and ranges between 10 and 80 cps.

Principles involved in hovering flight are as follows

1. During hovering, the weight of the hovering insect is acting downward, and it is balanced by a lift force given by the rate of change of momentum of air acting in an upward direction due to wingbeat cycle. The mass of the insect is usually small as compared to a bird or bat. The hovering equilibrium can be expressed as follows:

   $R = W$

   $W = Mf$

   $R = Mf$

   $R\alpha = dm/dt$

   R stands for reaction force.

   W indicates the weight of the hovering insect. Mf is the mass of the flier.

   dm/dt is the rate of the small mass of a quantity of air.

2. In the hovering state, the forward velocity is almost zero and hence $W = L$. The drag and thrust forces which are developed by the flapping flexible wings almost become equal to each other, contributing to equilibrium conditions in the hovering state.
3. Most of the aerodynamic work is done during the downstroke of the wingbeat cycle and the upstroke of the wing is assumed as more or less a recovery stroke which needs relatively less power. However, the wingbeat cycle, in general, depends on anatomy, physiology, elastic nature of the fulcrum (resilin), the structure of the flapping flexible wing and muscle type.
4. Biological flier which has higher body mass cannot hover for a longer time, since high power is not available to the muscle.
5. Hovering is a continuous power-on beating of the wings.
6. The flow of air through stroke plane in hovering state is mainly due to induced downward velocity.
7. The hovering state of the flier is calculated on the assumption of steady state of the air. Hovering in an unsteady state of air cannot be ruled out in nature. True hovering is different from wind-assisted hovering.
8. The wing tip during hovering flight traces a figure of '8'. The shape of figure of '8' is variable in different groups of insects. The figure of '8' can be explained by wing Lissajou's pattern.
9. In the case of Cicada (or hummingbird) while hovering, the flapping pattern is coupled with the wing pitch adjustment, leading to the formation of figure of 8.

10. High-frequency flapping wing sheds the vortex at the tip of the wings. These wing tip vortices accumulate one on the above as a cushion and press against the next flapping stroke during hovering.
11. Cicada is an ideal reference for hovering flight in insects because of its large weight to wing size ratio. Cicada is a fast flier.
12. Wingspan remains more or less constant during hovering.
13. Usually, the hovering frequency is high, and the variation in frequency range depends upon whether the insect is a neurogenic or myogenic flier.
14. The neurogenic nature of flier is not influenced by wing tip mutilations. However, in myogenic flier after wing tip mutilations, the frequency increases considerably.
15. Basically, the soapnut bug is a myogenic flier that has become neurogenic because of adaptation to the sedentary way of life on soapnut trees during the prolonged course of evolution.

Differences between Symmetrical and Asymmetrical Hovering (modified after Chari 2014).

S.No	Symmetrical Hovering	Asymmetrical Hovering
1	Common in Hummingbirds and some insects	Seen in Kestrels and Kingfishes
2	Body mass 2–30gm, flight position is vertical	Body mass is relatively high, flight position is horizontal
3	Wings move forward and backward and rotate at the base	Wings move up and down and do not rotate at the base
4	Differential lift is produced during each stroke	Most lift is produced during downstroke and upstroke is recovery stroke
5	Wings rotate at the fulcrum during pronation and supination	Wings do not rotate at the fulcrum
6	Hovering is due to wingbeat frequency and forward velocity is zero	Hovering is assisted by incoming wind also
7	Figure of ‘8’ is vertical in plane	Figure of ‘8’ is horizontal in plane
8	The wing is relatively rigid and chambered at the wing tip	During the upstroke, the wing, flexes and primary feather open up
9	In hovering insects, the lift produced may be 50% or more. In hummingbirds, the downstroke produces 70% lift	The lift produced during downstroke may be about 90% and the upstroke is a recovery stroke
10	Hovering frequency ranges from 10–80cps	The hovering frequency is low and is about 10–15cps

Fig. 6.1 Hovering insects. **a** Carpenter Bee. **b** Honey Bee

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Chapter 7
Moment of Inertia and Mutilation Studies of an Insect Wing

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Abstract Moment of inertial (MI) is the measure of resistance offered by a body to change the rotational movement about an axis. The MI graph describes spanwise distribution of wingmass and density. It forms the basis for the calculation of Kinetics of a moving body. Strip analysis method is used for calculating, strip loading and strip area. Study of MI, radius of gyration, kinetic energy, torque, and inertial power helps in designing micro bio aerial vehicles. In soapnut bug, cutting the length of the wing by 5–40%, increases the frequency by 50–110cps. Total energy has been calculated for single wing which is about 135Ergs. MI formulae have been suggested for different geometric shapes. Finally, translatory and rotatory motions have been elucidated.

Keywords Moment of inertia · Wing mutilation · Geometrical wing shapes · Torque · KE · Translatory and rotatory motions · Angular velocity

Introduction

The study of Moment of Inertia (MI) of an insect wing helps us in understanding Kinetic Energy (KE), torque (τ) and inertial power of the flier and properties of flight surface. The MI graph will indicate the overall distribution of the mass of the wing and density of the wing which decreases along the wingspan. MI study is important to describe the angular motion of biological fliers. We usually study MI of the wing with one degree of freedom; however, the wing moves in x, y and z directions in nature.

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Definition

Moment of Inertia is the measure of the resistance offered by a body to change the rotational motion about an axis. It forms the basis for the calculation of the kinetic energy of moving bodies. The general equation for the moment of inertia can be written as follows:

$$I = \sum_{i=1}^{n} m_i r_i^2 \tag{7.1}$$

where

m_i is the mass of the individual strip of the wings (gm).
r_i is the distance between wing fulcrum and centre of mass of the strip.
i Is the Strip Number.
n is the total number of strips.

Expression for Moment of Inertia

During a rotary or oscillatory motion, the expression from Eq. 7.1 gets modified to include the rotational effects. Then the kinetic energy of the oscillating or moving wing can be expressed as

$$KE = \frac{1}{2} I w^2 \tag{7.2}$$

and

$$w = 2\pi \vartheta \tag{7.3}$$

where

I is the moment of inertia of the wing.
w is the angular velocity of wingbeat indicating angular movement during flapping (rad/s).
ϑ is the wingbeat frequency of the flier (cps).

$$\therefore KE = \frac{1}{2} I (2\pi \vartheta)^2 = 2\pi^2 I \vartheta^2 \tag{7.4}$$

Note that I and MI are synonymous in this chapter/book.

Expression for Rotational Kinetic Energy

In the case of a flapping wing, the kinetic energy possessed by the wing is due to the rotational energy.

$$\text{Rotational Kinetic Energy } (KE) = \frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2 + \frac{1}{2}m_3v_3^2 + \cdots$$

where $v = r.w$

$$KE = \frac{1}{2}m_1w^2r_1^2 + \frac{1}{2}m_2w^2r_2^2 + \frac{1}{2}m_3w^2r_3^2 + \ldots$$

$$= \frac{1}{2}w^2\left(m_1r_1^2 + m_2r_2^2 + m_3r_3^2 + \ldots\right)$$

$$= \tfrac{1}{2}w^2 \sum_{i=1}^{n} m_i.r_i^2 = \tfrac{1}{2}w^2.I \text{ (from Eq. 7.1)}$$

$$\therefore KE = \frac{1}{2}I.w^2 \tag{7.5}$$

The quantity I is called the moment of inertia. The moment of inertia is calculated about the fulcrum of the moving bodies. Usually, a single unfolded wing is considered for the calculation purpose. The wingspan (wing length) of the insect has a bearing on the disc area and also influences the wing loading.

Computation of Moment of Inertia of an Insect Wing

The kinetic energy is required basically to accelerate the wings at each stroke. This is also known as the inertial power which can be calculated. The inertial power helps in understanding the energy expended by the insect for flight. In order to determine the inertial power, the MI of the wing is calculated about an axis parallel to the wing surface passing through the point of articulation of the wing with the body.

The moment of inertia about a given axis takes into account the distribution of mass and area about the axis of rotation or oscillations and plays a vital role in the angular movement of the flexible wings. In the context of Entomology, these are conventionally termed as the linear and rotational motion of the wings. It should be clearly stated that the inertial power is that component of power which is associated with the acceleration and retardation of wing movements. In most of the insects when they are flying slowly, the angular velocity may not change significantly. Due to the movement of the wing, a force field is generated which consists of a resultant force and a couple. This force is responsible for the lift and thrust and the couple is responsible for the wing rotation and twist. It is usually assumed that the upper part of the wing adjoining the fulcrum is responsible for the development of lift and the next part, which is relatively thin and membranous, is responsible for the thrust. The wingtip which is very thin being the last part contributes to the induced drag through the formation of vortices and also contributes to the downwash and forward motion.

In order to overcome the rotation, the wings of the flying insects generate a figure of "**8**" or ellipse in space at the wingtips during the wingbeat cycle. This is because of the superimposition of two Simple Harmonic Motions (SHM) in flapping and twisting modes. The different segments of the wings perform different functions during flapping through aeroelastic interactions including structural deformations. This division of labour is an interesting example of morpho-functional correlation. Lift, thrust and induced drag as developed by various components of the flapping wings are notable features. It has to be emphasized that there is a closer correlation between the structure and functions of insect flapping wings as compared to man-made aeroplane and helicopter wings, which have limited capability.

The energy required to move the insect wings is supplied by the contraction of flight muscles of the insect, where the ATP (Adenosine Tri-Phosphate) gets hydrolyzed. Due to this action of the enzyme ATPase, ATP gets converted into ADP, inorganic phosphate with associated energy release. In insect wings, the wing motion is more or less sinusoidal. The resilin at the wing base works as an elastomere. The elastomere is four times more elastic than conventional rubber and plays a vital role in the insect flight. If the resilin is cut, the insect is unable to fly. This resilin is the characteristic elastomere found only in insects and other arthropods and not in homeothermic fliers such as birds and bats.

The concept of the centre of mass will help in a better understanding of the wing dynamics and Moment of Inertia computations as described in Appendix. The general expression for the moment of inertia is given in Eq. 7.1. Detailed studies carried out by Prof. N. Chari and Prof. M. Prasad at SNIST, Hyderabad, indicate that the wingspan, in general, increases with the mass of the flier, but up to a value of about 0.65 to 0.95 gm. It has been observed from various studies that the mass of ***T. javanica*** varies from 0.45 to 1 gm in Telangana, India. A further increase in the insect mass beyond this value restricts the wingspan typically at around 5.85 cm. The wing breadth only increases to provide the necessary wing area to support the flight and associated aerodynamic forces.

During mutilation studies as mentioned earlier [1], the wing was cut into 10 equal strips and the typical wing length was 21.5 mm. The values of strip wing loading and strip area as calculated and measured for various strips numbering from 1 to 10 are shown in Fig. 7.1. These studies also further indicate that the area of the strips is nearly a maximum for strip numbers 2–5 beyond which the area seems to decrease, indicating a decrease in area and mass as well.

The MI of the moving wing is usually calculated by the strip analysis method. The wing is carefully cut at the fulcrum where it is attached to the thorax. Subsequently, this wing is carefully cut into as many equidistant strips as possible (typically 10 strips). The strips are numbered in increasing order from the fulcrum to the wingtip. The distance is measured from the fulcrum point to the centreline of each strip.

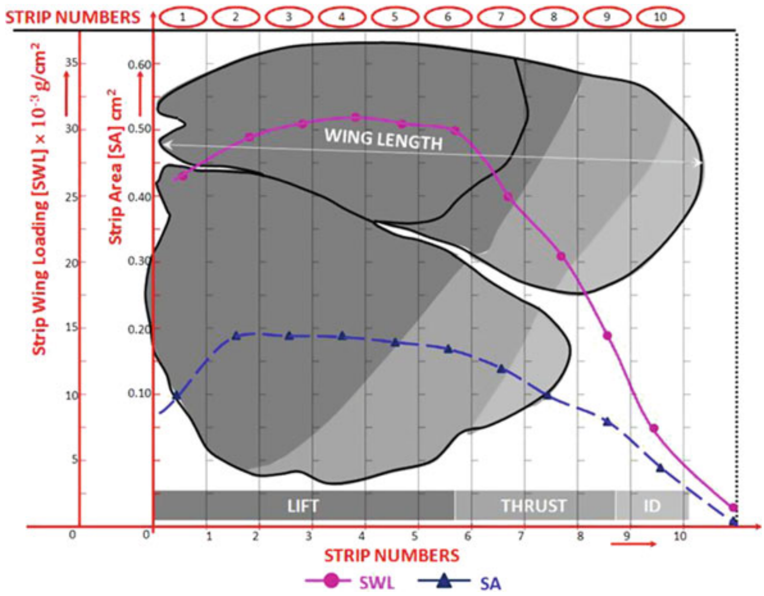


Fig. 7.1 Strip method used for calculating wing loading and strip area

The weight of each strip is determined carefully by using a sensitive balance, which can measure up to 1 mg. The total moment of inertia of the wing is calculated by summing the moments of inertia of the individual strips. Additional data relating to the wings in terms of stripwise wing mass and moment of inertia are shown plotted in Fig. 7.2. The force field operating above the wing is the resultant of the forces acting on several strips of wings. It may be noted that the wing areas alter slightly during the downstroke and upstroke since the insect wings are anisotropic and due to the flexible and membranous nature of the wings. This phenomenon also contributes to the complex aeroelastic behaviour during insect flight. It should be noted that we are dealing with chitinous thin, flapping flexible wings whose areas are slightly variable during the down and upstroke with added rotary and twisting motion of the wings. This makes the exact analysis of the flight and the wing motion more complex.

In ***T. javanica***, the total wing mass is 6 mg while the total moment of inertia of each wing is typically 6000×10^{-6}gm cm^2 with reference to the *y*-axis passing through the origin. Preliminary investigations were carried out by Chari and his research associates at Kakatiya University, Warangal, India. Detailed calculations for a typical insect such as ***T. javanica*** have been carried out by the present authors at SNIST, Hyderabad. This data forms the basis for the present discussion.

$$\left(\bar{l}\right) = \sqrt{(\mathrm{I/m})},\ \text{where I} = \text{Total Moment of Inertia}$$

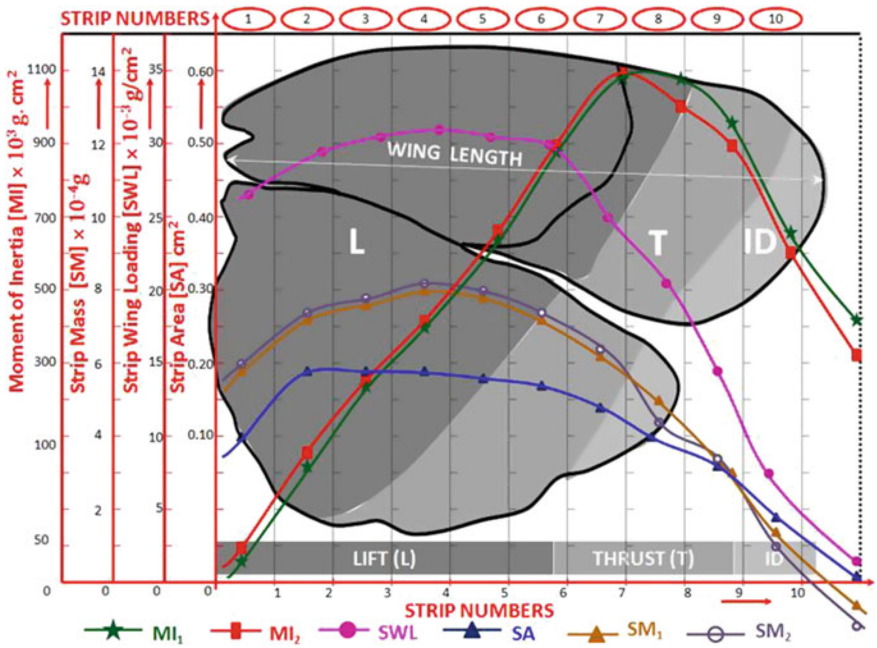


Fig. 7.2 Strip method for calculation of moment of inertia (MI)

$$\bar{l} = \sqrt{\frac{1}{m}} = \sqrt{\frac{6000 \times 10^{-6}}{60 \times 10^{-4}}} = \sqrt{100 \times 10^{-2}} = 1 \text{ cm}$$

The effective radius of gyration $\left(\bar{l}\right)$for the total wing is observed to be 10 mm i.e. 10 mm

Thus, the effective radius of gyration for the wing is 10 mm or 1 cm from the fulcrum. A detailed study of the thickness, density and mass distribution across the wingspan of the insect wing as discussed here will be an added asset, while attempting the selection of the material design of the MAVs.

Comments on the Moment of Inertia Studies

The moment of inertia studies on the insect wing *T. javanica* can be summarized as follows:

1. The MI graph describes the spanwise distribution of the wing mass and wing density. It may be observed that the mass decreases gradually as one moves away from the fulcrum towards the wingtip.

2. Knowledge of the MI also helps in describing the acceleration and deceleration pattern during the angular motion of the wing.
3. A 3-D study including the wing thickness variation along the wingspan gives more specific information needed for the design of membranous wings for MAVs.
4. Modern techniques like zooming and the use of a nano-balance will be an added advantage during experimentation as the total mass of each wing is less than 10 mg and each strip is about a milligram or so. Such studies will yield more accurate data for the MAV/ NAV Design.
5. The moment of inertia around the axis is $I = mK^2$
   where K is known as the radius of gyration.
6. Study of MI and the radius of gyration is also necessary to calculate KE, torque and inertial power requirements in connection with MAV/ NAV flight studies.
7. The moment of Inertia data is very much helpful in the experimental evaluation of the wingbeat frequency of an individual flier as well as for the comparison with the other species for possible generalization of such studies.

Mutilation Studies of Insect Wings

Mutilation studies of insect wings were carried out by various researchers both on neurogenic and myogenic fliers. The neurogenic fliers are also known as synchronous fliers where the wingbeat frequency usually varies from about 2–100 Hz. The myogenic fliers are also known as asynchronous fliers, where the wingbeat frequency varies from 100 to 1000 Hz. These studies have been in the tethered state.

It was observed that in the case of neurogenic fliers, if we cut the wings inwards from the wingtip, the frequency of wingbeat does not increase. In myogenic fliers, however, the frequency of the wing after mutilation gradually increases so long as the coupling between the wings is not affected. Further, if the wing coupling is destroyed during cutting, both the wings start moving independently. It may be observed that the female fliers have relatively higher mass (by 20% approx.) and higher wingbeat frequency (by 10% approx.) compared to male counterparts (Fig. 7.3).

For a myogenic flier like ***Tessaratoma javanica***, the wing mutilation studies show that a decrease in wing length by 5–40% and breadth 1–28% leads to doubling in frequency from 55 to 110 Hz (Fig. 7.3). The typical weight of the insect under study was 940 mg and in another case, the weight was 1130 mg. The present studies indicate that a variation in aspect ratio for the wing may create additional aeroelastic problems due to increased wingbeat frequency. The decrease in strip area has been depicted in Fig. 7.4.

Further, it may be stated from the wing analysis of the loading experiments on *T. javanica* conducted in 1975, by increasing the wing loading gradually in steps of 0.5 mg at the wingtip to an extent of 7 mg, the wingbeat frequency was observed to decrease by almost 50% in tethered flight. This aspect has to be carefully studied

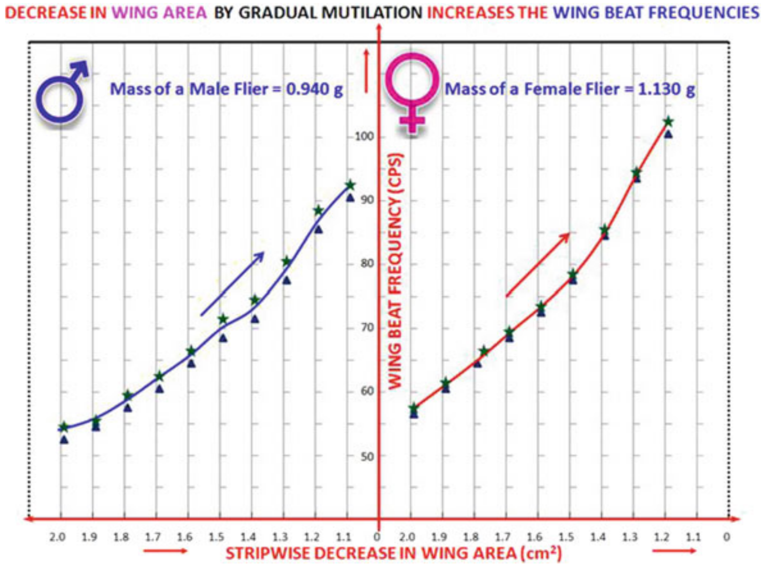


Fig. 7.3 Variation of wingbeat frequency with mutilation (*T. javanica*)

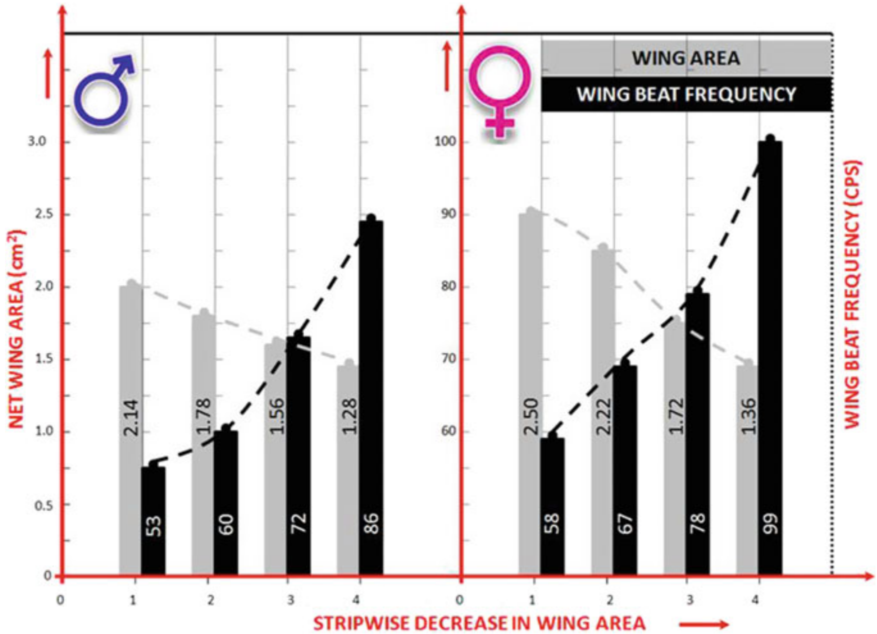


Fig. 7.4 Variation of wingbeat frequency with wing area after gradual mutilation (*T. javanica*)

further due to its great significance in the design of bio-mimicking Insect-based MAVs (Chari. N–Personal Communication).

It may be mentioned that these experiments have been carried out in a tethered state of the insect by using a stroboscope and the frequency values were also confirmed by applying Mass Flow Theory. The bio-acoustic analysis of the frequency of the mutilated fliers can also be done by feeding the sound to a Cathode Ray Oscilloscope (CRO) through a microphone and recording the flight pattern of the wing for subsequent Fourier analysis studies. The main aim of the mutilation experiments is to know how the various sections of the wing contribute to the development of aerodynamic forces indirectly by comparing them with normal ones.

It has to be mentioned that ***T. javanica*** has a wingbeat frequency of 50 Hz and still we classify it as a myogenic flier though ***T. javanica*** belongs to Pentatomidae. These bugs, because of their sedentary lifestyle, secondarily, have reduced their frequency of flight during the course of evolution lasting from Eocene (period covering about 60 million years). However, surprisingly, the muscles still retain their myogenic structure. This might be due to some disuse atrophy effect on the wingbeat frequency during the prolonged course of evolution due to sedentary feeding habits of ***T. javanica*** on the soapnut and other related trees.

At this juncture, it may be summarized that the insect once mutilated is not able to fly in nature with mutilated wings. Similarly, wingtip loading was done on ***T. javanica*** by fixing an additional mass of about 7 mg (in steps of 0.5 mg) to the wingtips to know the effect of wingtip loading. It was observed that the wingbeat frequency decreases by about 50% in such cases. Such experiments on ***T. javanica*** would help in the designing of MAVs with wings of lower frequency.

A positive correlation exists between the increasing mass of the flier and increasing wingspan as shown in Fig. 7.5. By careful observations, it can be noticed that the wingspan values do not increase further beyond a mass of 1 gm. With a further increase in mass, an increase in the value of effective breadth cannot be ruled out to cater to the flight requirement. The wingspan value plays a vital role in understanding the MI and the wingbeat frequency of insect wings.

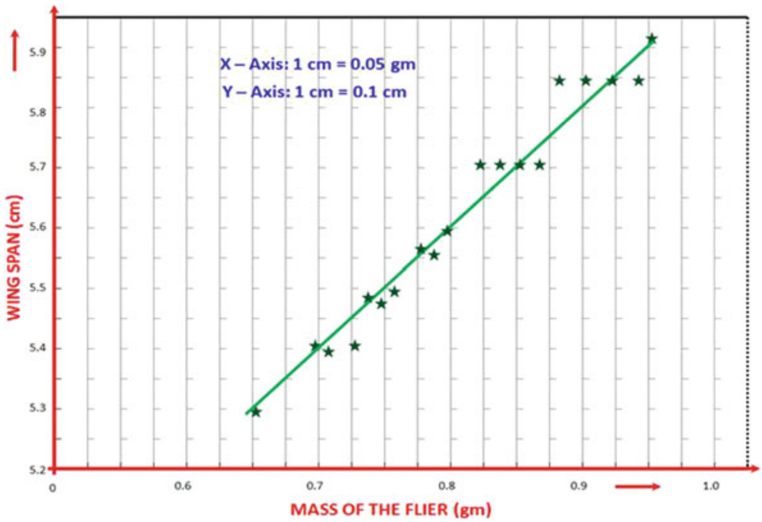


Fig. 7.5 Mass versus Wingspan in *T. javanica*

Summary

The moment of inertia and the mutilation studies together help in understanding the structural design and relative functioning of various components of the flapping wing of the insect flier in relation to aerodynamic forces. However, mutilation studies offer a negative approach. Increasing the wing mass by local addition of weight at the wingtip helps in decreasing the wingbeat frequency of the flier. These studies in general may contribute to the design of MAV wings. MI helps in determining the torque needed for a desired angular acceleration about a rotational axis. For a three-dimensional movement, the matrix should be diagonal and torque around should act independently as in the case of biological wing movements.

Appendix

This part of the appendix is extracted and modified from "*Properties of Matter*" written by P. E. SubramaniaIyer [3]

Energy of a Particle Executing Simple Harmonic Motion

$$\frac{d^2x}{dt^2} = -\omega^2 x \text{ (Linear Motion)}$$

If m—the mass of the particle and x—displacement,

the force necessary to produce this acceleration is $m\frac{d^2x}{dt^2}$.

If it undergoes a small additional displacement dx, work done by the force for producing the additional displacement is given by

$$dw = F.dx = \omega^2 m.x.dx$$

Assuming that the whole of the displacement is produced this way, the work done is

$$\int dw = \int_0^x \omega^2 m.x.dx = \frac{1}{2}\omega^2 m x^2$$

This work gives the potential energy of the particle at that instant. The instantaneous velocity, v, of the particle is given by

$$v = \frac{dx}{dt} \text{ and } P.E = \frac{1}{2}\omega^2 m x^2$$

$$v^2 = \omega^2\left(a^2 - x^2\right)$$

where a—amplitude of the Simple Harmonic Motion (S.H.M) and hence

$$v = \omega\left(\sqrt{a^2 - x^2}\right) \tag{7.6}$$

The kinetic energy of the particle at that instant is equal to $\frac{1}{2}mv^2$

$$K.E = \frac{1}{2}m\omega^2\left(a^2 - x^2\right)$$

The total energy of the particle at the instant is

$$= \frac{1}{2}\omega^2 mx^2 + \frac{1}{2}\omega^2 m\left(a^2 - x^2\right)$$

$$\textbf{\textit{Total Energy}} = \frac{1}{2}\boldsymbol{\omega}^2 \boldsymbol{ma}^2 \tag{7.7}$$

The $\omega = \frac{2\pi}{T}$ and $\omega^2 = \left(\frac{2\pi}{T}\right)^2 = \frac{4\pi^2}{T^2}$, where T = time period or time taken for one cycle.

The total energy of the particle is given by

$$\boldsymbol{E} = \frac{2\boldsymbol{\pi}^2 \boldsymbol{ma}^2}{\boldsymbol{T}^2} \tag{7.8}$$

Thus, the total energy E at any instant is constant and independent of local displacement x for small amplitudes.

If ϑ be the frequency of the particle, $\vartheta = \frac{1}{T} = \frac{\omega}{2\pi}$

$$\therefore \textbf{\textit{Total Energy of particle}}\ (\boldsymbol{E}) = 2\boldsymbol{\pi}^2 \boldsymbol{ma}^2 \vartheta^2 \tag{7.9}$$

Moment of Inertia

The Moment of Inertia of a body depends on

(a) Mass of the body and
(b) The distance of the mass from the axis of rotation

$$\boldsymbol{I} = \textbf{\textit{mass}} \times (\textbf{\textit{radius of gyration}})^2 \tag{7.10}$$

The radius of gyration, k, is the distance of the centre of mass from the fulcrum.

The dimensional formula for the moment of inertia is $I = Mk^2$.

Comparison between Translatory and Rotary Motions is presented in Table 7.3 at the end.

Example 1—Case of an Insect Wing (*T. Javanica*)

Mass of the wing = 10 mg

Wingbeat Frequency $\vartheta = 50$ cps

Maximum Amplitude about the mean is $45^0 = 45^0 \times \frac{\pi}{180} = 0.7854$ rad (Typically)

Total Energy $E = 2\pi^2 m\vartheta^2 a^2$

By considering $\theta = 30^0 = \frac{30}{180} \times \pi = \frac{\pi}{6}$radians ; $a = r\theta = 1 \times \frac{\pi}{6} = 0.5236$ cm.

Here, we considered $r = 1$ cm as the distance of centre of mass of the wing from the fulcrum.

$$= 2 \times \pi^2 \times 10 \times 10^{-3} \times 50^2 \times (0.5236)^2$$

$$\therefore \text{Total Energy} = 135 \text{ Ergs}$$

Total energy values are computed for different amplitudes of θ ranging from 0^0 to 60^0 as shown plotted in Fig. 7.6. The total energy spent by the insect is seen to increase with the rise in θ.

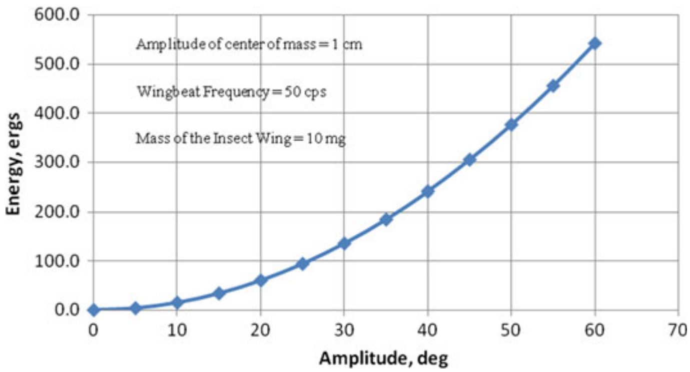
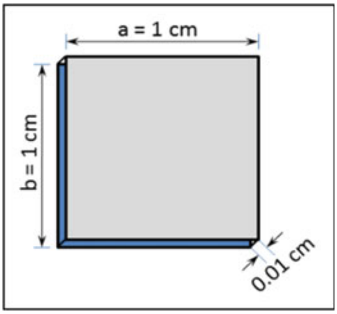


Fig. 7.6 Energy values for different amplitudes of $\boldsymbol{\theta}$

Example 2—Case of an Aluminium Foil

Aluminium foil thickness is 100 μ = 0.01 cm



Density ≈ 2.8 gm/cm^3
Weight = 2.8 × 0.01 = 2.8 × 10^{-2}gm
Weight = 28 mg
Wingbeat Frequency $\vartheta = 50$ cps

$$a = r \cdot \theta$$

k = radius of gyration

$$I = \frac{Mb^2}{3}$$

$$= Mk^2$$

$$r = \frac{b}{\sqrt{3}}$$

If $\theta = 30^0$

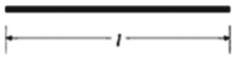
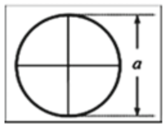
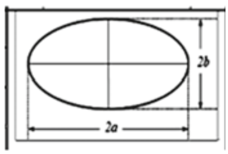
$$\therefore a = \frac{1}{\sqrt{3}} \times \frac{30}{180} \times \pi = 0.302 \text{ cm}$$

$$E = 2\pi^2 ma^2\vartheta^2 = 2 \times \pi^2 \times 0.028 \times \left(\frac{1}{\sqrt{3}}\right)^2 \times 50^2$$

$$E = 460.15 \text{ ergs.}$$

See Tables 7.1, 7.2, 7.3

Table 7.1 Moment of Inertia of Regular Bodies about Different Axis

SI. no	body	Position of axis of rotation	Moment of inertia	Shape
1	Thin bar	a. Through centre of gravity and perpendicular to length	$\frac{Ml^2}{12}$	
		b. Through one end and perpendicular to its length	$\frac{Ml^2}{3}$	
2	Rectangular Lamina length: = a; breadth = b	a. Passing through center of gravity and perpendicular to its plane	$M\left(\frac{l^2+b^2}{12}\right)$	
		b. About an axis in its own plane and passing through one if its ends parallel to x-axis	$I_z = \frac{Mb^2}{12} + M\left(\frac{b}{2}\right)^2$ $I_z = \frac{Mb^2}{3}$	
		c. About an axis in its own plane and passing through one if its ends parallel to y-axis	$I_y = \frac{Ma^2}{12} + M\left(\frac{a}{2}\right)^2$ $I_y = \frac{Ma^2}{3}$	
3	Circular lamina	a. About any diameter	$I_D = \frac{1}{4}MR^2$	
		b. About a tangent in its plane	$I_\tau = I_D + M.R^2$ $= \frac{1}{4}MR^2 + MR^2 = \frac{5}{4}MR^2$	
4	Elliptic lamina	a. About the major axis (2a)	$I_z = \frac{1}{4}Mb^2$	
		b. About the minor axis (2b)	$I_y = \frac{1}{4}Ma^2$	
		c. About axis tangent at the edge in its own plane parallel to major axis	$I_{\tau x} = \frac{1}{4}Mb^2 + Mb = \frac{5}{4}Mb$	

(continued)

Table 7.1 (continued)

SI. no	body	Position of axis of rotation	Moment of inertia	Shape
		d. About axis tangent at the edge in its own plane parallel to major axis	$I_{\tau y} = \frac{1}{4}Ma^2 + Ma^2 = \frac{5}{4}Mb^2$	

Table 7.2 Average experimental wing data observed for six different ***Tessaratoma javanica*** insects

S. no	Parameters	Units	Male			Female		
			1 M	2 M	3 M	4F	5F	6F
1	Total wing strip area	cm^2	2.109	2.070	1.914	2.280	2.439	2.474
2	Total strip loading	gm/cm^2	148.61	169.98	190.98	225.00	225.98	228.00
3	Total wing strip mass	$\times 10^{-3}$ gm	60.25	59.99	59.98	80.02	80.00	89.99
4	Wing strip density	$\times 10^{-3}$ gm/cm^2	2.86	2.90	3.13	3.51	3.28	3.23
5	Moment of inertia	$\times 10^{-6}$ gm cm^2	6012.41	6040.15	6297.18	9014.93	9004.06	9939.63
6	Moment of inertia (external)	$\times 10^{-6}$ gm cm^2	5848.05	5956.15	6111.64	8105.19	8032.25	8658.24
7	Wing strip mass (actual)	$\times 10^{-4}$ gm	59.97	59.99	59.96	79.99	79.98	89.98
8	Mass of flier	gm	0.624	0.704	0.730	1.025	1.104	1.130
9	Wingbeat frequency (ϑ)	cps				60		
10	Wingspan (L)	cm	5.2	5.4	5.5	6.0	6.0	6.0
11	Wing breadth (B_{eff})	cm	1.0	1.10	1.11	1.21	1.20	1.20

The basic information was extracted from Ph.D. Thesis of [4]

Table 7.3 Comparision between translatory and rotary motions

Translatory motion				Rotary motion			
Parameters	Symbol	Formula	Units	Parameters	Symbol	Formula	Units
Displacement(S)	S	–	cm	Angular Displacement	θ	–	rad
Velocity	V	V = d/t	cm/s	Angular Velocity	ω	$\omega = \frac{d\theta}{dt}$	Radians /sec
Acceleration	a	$\alpha = \frac{dv}{dt}$ or $\frac{d^2s}{dt^2}$	cm/s^2	Angular Acceleration	α	$\alpha = \frac{d\omega}{dt}$ or $\frac{d^2\theta}{dt^2}$	$\frac{Radian}{Sec^2}$
Mass	M	–	gm	Moment of Inertia	I	$I = MK^2$	$Kg{\cdot}m/S^2$
Force	F	F = m a	dyne	Torque or Couple	C	C = I α	$Ra{\cdot}Kg{\cdot}M^2/S^2$
Momentum	P	P = m ·v	gm·cm/s	Angular Momentum	L	L = I·ω	rad $-Kg{\cdot}m^2/s$
Work	W	W = f·d	$gm{\cdot}cm^2/s^2$	Work	W	C.θ	
Kinetic Energy	K·E	K·E = 1/2 mv2	erg or $g{\cdot}cm^2/s^2$	Kinetic Energy	K·E	$K.E = \frac{1}{2}I\omega^2$	Joule

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Chapter 8
Chitinous Membranes and Analogous Material

N. Chari, Sesha Srinivas Vutukuru, R. Saicharan, and A. Uma

Abstract Chitin is considered to be an important natural polymer with a long chain of *N*-acetylglucosamine found in exoskeleton of insects and membranous wings. Basic structure of insect integument with trichobothrium has been illustrated. Chitin is common in Arthropoda (Exoskeleton). Resilin is a protein polymer having 620 amino acids. It is present at the wing joint and is four times more elastic than rubber. Chitin and resilin have real importance in industry and biomedical applications. Resilin can be regenerated by genetic engineering. Silk is an important natural raw material for textiles. Silk fibre has 80% fibroin and 20% sericin. Sericulture is a labour industry suited for rural areas in India. Spider silk can also be produced by genetic engineering. Its bullet proof nature is a notable feature. Spider is included for comparison of fibre with insect silk and for its unique elastic properties.

Keywords Chitin · Polymer · Resilin · Elastomere · Silk · Fibroin · Sericin · Genetic engineering

Introduction to Chitin

Chitin is considered to be the important natural polymer with a long chain of *N*-acetylglucosamine which is a derivative of glucose. It is also considered to be the second most important polymer in nature after cellulose and can be obtained as a cheap renewable polymer from marine crustaceans, shrimps and crabs [1]. Chitin is found in the cell walls of fungi, exoskeletons of arthropods and insects, radulae of molluscs and internal shells of cephalopods. Reflective materials like (iridophores) in the epidermis and the eyes of arthropods and cephalopods also contain chitin. It

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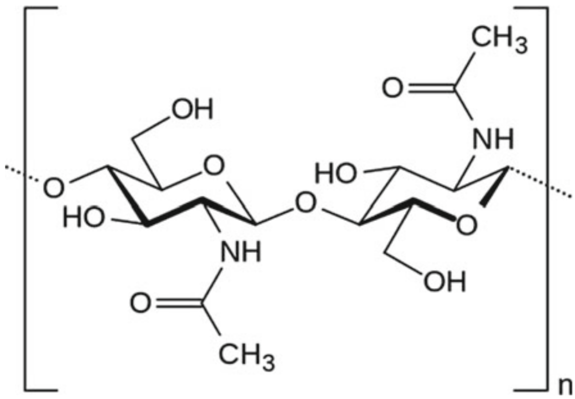
Fig. 8.1 Chemical structure of chitin poly (β-(1–4)—*N*-acetyl-D-glucosamine)



is also known as the most renewable biopolymer. The chemical representation of chitin is given by $(C_8H_{13}O_5N)_n$ and is a natural polysaccharide having a linkage of (β-(1–4)–*N*-acetyl-D-glucosamine) and is also represented by (GlcNAc) [2]. Chitin was discovered and named as *fungine* by Henri Braconnot, a French Professor, in 1811. It has also been reported in the literature from the eggshells of nematodes, leguminous plants, Rhizobium and even in vertebrates during the early stages of embryogenesis.

The structure of the chitin molecule in Fig. 8.1 shows two of the *N*-acetylglucosamine units that repeat to form long chains in β-1, 4 linkages.

Structure of the Insect Integument

The insect integument is made up of the following layers:

1. A thin non-cellular basement membrane that lines the body cavity of the insects.
2. An epithelial layer composed of small cylindrical flattened cells with a distinct central nucleus.
3. External to the epidermis, the adjacent layer is known as the procuticle, which is further subdivided into endochitin and exochitin. Sometimes, there may be an ill-defined third layer known as mesochitin; however, the mesochitin is not found in all insects. Differentiation of exocuticle involves sclerotization, where the chitin layer becomes relatively hard.
4. The procuticle layer contains a matrix of proteins having many microfibres of chitin. The chitin is layered in the form of lamellae. The endocuticle and exocuticle are made up of microfibres.
5. The orientation of microfibres differs in endocuticle and exocuticle.
6. An oriented monolayer of wax exists above the epicuticle. It acts as a chief barrier to the movement of water into and out of the insect body. The wax layer consists of a long chain of hydrocarbons and esters of fatty acids and alcohols.

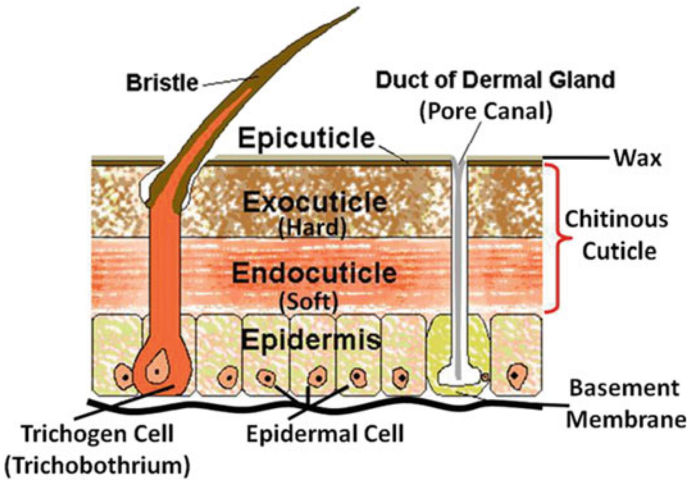


Fig. 8.2 Basic structure of insect integument (diagrammatic representation from various sources)

The wax layer is present on the abdomen and thorax of pentatomide bugs such as ***Tessaratoma javanica*** (TJ). The wax is also present in some Fulgoroidea, scale insects and also in honey bees which secrete a large amount of wax which helps in making a honeycomb.

7. A trichogen cell is a hair-like sensory projection of the cuticle articulated by a socket. At the base of the trichogen cell is a nerve ending. Larger hairs and bristles are the products of specialized epidermal cells [3] (Fig. 8.2).

Based on the sources of chitin, it has two allomorphs in the forms α and β. These are studied by using infrared and solid-state NMR spectroscopy along with X-ray diffraction. However, there is a third allomorph, γ-chitin, available in various resources, but reported to be a variant of α-family, and hence it is least considered. The α-form is more common in chitinous cuticles, whereas the β and γ forms are usually found in cocoons [4]. α, β and γ forms of chitin mainly differ in the degree of hydration, in the size of the unit cell and in the number of chitin chains per unit cell [5, 6].

The β-chitin anhydrous structures seem to be well established and stable but remain to be uncertain due to sensitivity towards hydration. Considering this view, β-chitin may not be suitable for the design of flexible flapping wings.

Properties

Chitin's physical properties in its pure form include translucent, pliable, resilient and tougher. The chitin along with calcium carbonate (chitosan) is much stronger and has a wide range of biomedical and bio-physical applications. A caterpillar integument consists of pure and composite forms of chitins to give maximum flexibility to the body and due to which it can move easily.

Chitin will not be soluble in the water but soluble in sodium hydroxide and potassium hydroxide solutions at 160–180 °C. It gives a complex derivative known as chitosan which is stained brown by iodine. Dilute sulphuric acid also gives the chitosan reaction.

The chitin microfibrils are embedded into the protein matrix firmly, resulting in the formation of endochitin and exochitin. In peritrophic membranes, the microfibrils are normally arranged as a network in the amorphous matrix [7].

In the form, all chains of chitin exhibit an anti-parallel orientation. This orientation allows tight packaging into chitin microfibrils that are stabilized by a high number of hydrogen bonds. This arrangement may contribute to mechanical strength [8]. In the form, the chains are arranged in a parallel manner. In the form, sets of two parallel strands alternate with a single anti-parallel strand and chains are moderately less packed than form with the reduced number of inter-chain hydrogen bonds and are able to react with water. The high degree of hydration and reduced packaging help soft chitinous structures such as peritrophic matrices and cocoons.

The chitin microfibrils are embedded into the protein matrix and stabilize it in a way that resembles constructions of steel-reinforced concrete complex patterns and textures [9]. By contrast, in peritrophic matrices, the microfibrils are normally arranged as a network of randomly organized structures [7]. Insect cuticles form an exoskeleton to keep body growth under the influence of moulting hormones.

Applications of Chitin

Recent studies have revealed that chitin is a good inducer for defence mechanisms in various plants, and hence, it can be used as a fertilizer to improve crops.

It is widely used in various industries for different applications such as food processing. Chemically modified chitin helps in forming edible films to stabilize foods and pharmaceuticals. It is also used as a binder in dyes, fabrics and adhesives and also in the paper industry.

In recent times, many researchers delivered a reproducible form of bio-degradable plastic that finds usage in 3-D bio-printing.

It is used as a surgical thread due to its flexibility and bio-degradability [2]. Chitin may increase the allergies in human beings and animals. However, it has to be emphasized that many insects are eaten by animals including human beings.

Exoskeletal chitin mass appears to increase at a lower rate with mass in flying insects as compared to non-flying insects.

Chitin-chitosan material is used as a bone filling material.

Chitin-oligomers have been claimed as anticancer drugs.

The Mechanical Properties of chitin are favourable in applications involving various levels of designs, viz. the exocuticle of crab has very high hardness.

The wet samples of chitin have higher strength and toughness as compared to dry samples.

Apart from all the above-known applications, chitin can also be used for making a streamlined body of fliers. The thin membranous flexible wings can also be designed from chitin. These wings can be attached to the body by using available commercial resilin depending on the frequency characteristics and power available of the system under design.

Applications of chitin depend on account of its bio-degradability, non-toxicity, physiologically being neutral, antibacterial, gel-forming affinities and affinity for proteins.

Analogous Materials

Resilin

Resilin is an elastomeric protein found in insects, in the tendons and at the wing hinges. Thus, it helps insects for jumping and to move their wings efficiently. Resilin and chitinous cuticles together form a composite structure for energy storage needed in the jumping of hoppers (insects). The catapult mechanism of rubber-like protein as an elastomere is a notable feature. Resilin was discovered by Torkel [16] from locust wing hinges as a rubber-like cuticle. Later, resilin was also found in the salivary glands of assassin bug and in the feed organs of these insects. It has also been reported in the case of Cicada and also in soapnut bugs, which have resilin in their sound-producing tymbals. A resilin-chitinous cuticle also would prevent structural failures and contribute to improved fatigue. Recently, resilin has been reported in flapping wing membranous as in small patches.

Resilin plays a vital role in insect hinges and also for jumping action in small insects. It stores energy for achieving jumping locomotion. The storage capacity for resilin is 10^6 w/kg and for direct muscle contraction is about 250 W/kg [10].

Considering the resilin to be loaded in pure compression, elastic potential energy U_e stored is given by

$$\text{Energy } (U_e) = \frac{EA}{2L}\delta L^2 \tag{8.1}$$

where

E is Young's modulus for resilin.
A is cross-sectional area of resilin part.
L is resting length of resilin part on the load.
δL is the change in length of resilin under full compression at the time of the jump.

Here, Young's modulus (E) is given by

$$E = \frac{\text{Tensile Stress}}{\text{Extensional Strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A_o}{\Delta L/L_o} = \frac{FL_o}{A_o \Delta L} \tag{8.2}$$

where

F is the force exerted on an object (resilin) under tension.
A_o is the original cross-sectional area at the side where force is applied on the resilin.
ΔL is the change of length in resilin.
L_o is the original length of resilin.

Force exerted by stretching or contracting the resilin is given by using Young's modulus of material under specific strain conditions as follows:

$$F = \frac{EA_o \Delta L}{L_o} \tag{8.3}$$

However, Hooke's Law describes the stiffness of a spring material, and from Eq. 7.3, we can derive the parameters of Hooke's law as follows:

$$F = \left(\frac{EA_o}{L_o}\right) \Delta L = kx \tag{8.4}$$

Here, Hooke considered $\left(\frac{EA_o}{L_o}\right)$ as k and ΔL as x.

From the above equations, it is possible to calculate the elastic potential energy stored in chitin by taking the integral of Eq. 7.3 with respect to its length, L, as follows:

$$U_e = \int \frac{EA_o \Delta L}{L_o} d\Delta L = \frac{EA_o}{L_o} \int \Delta L \, d\Delta L = \frac{EA_o \Delta L^2}{2L_o}$$

$$U_e = \frac{EA_o \Delta L^2}{2L_o} \tag{8.5}$$

where

U_e is considered as elastic potential energy.

Here, it is also possible to calculate the elastic potential energy per/unit volume as follows:

$$U = \frac{U_e}{A_o L_o} = \frac{E \Delta L^2}{2L_o^2} = \frac{1}{2} E \varepsilon^2 \tag{8.6}$$

where $\varepsilon = \frac{\Delta L}{L_o}$ = strain in the resilin.

However, Eq. 7.6 can also be expressed as integral of Hooke's law as

$$U_e = \int kx.dx = \frac{1}{2}kx^2 \tag{8.7}$$

The above mathematical expressions will help in understanding the physico-mechanical properties of resilin, which are quite complex.

Structure of Resilin

Some parts of the insect cuticle undergo elastic deformations during locomotion. In Fig. 8.3, the TS of wing hinge ligament of ***Schistocera gregaria*** has been enlarged by using a light microscope. The relation of exocuticle to endocuticle to fibrous protein and epidermis can clearly be seen. Resilin is found in between the two cuticle layers and is in contact with the epidermis.

Resilin consists of a protein having 620 amino acid molecules long chain included with a signal peptide of 17 residues at N-Terminus. This protein is secreted in the extracellular space. Its relative molecular mass is 56,771 daltons and its isoelectric point of 5.0 is composed of three domains. Resilin exhibits elasticity due to the cross links, which are composed of dityrosine and trityrosine. It also possesses fluorescent properties. Dityrosine, trityrosine and resilin emit a blue fluorescence when treated by Ultraviolet (UV) light [11]. The elastic efficiency of resilin has been reported from locust tendons by isolation of the protein. It is unaffected by deep freezing and

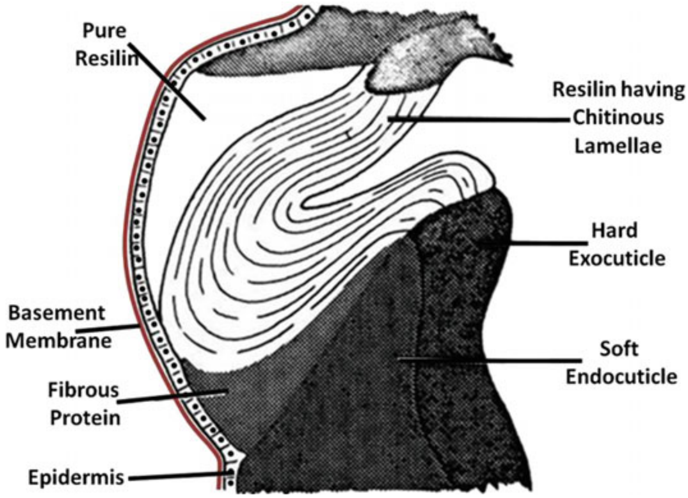


Fig. 8.3 Basic structure of wing hinge (TS) (modified after [3, 12])

also at temperatures up to 125 °C. It is also degraded by proteolytic enzymes as other proteins. The fluorescent properties have been reported to be pH dependent.

Genetic Engineering

Resilin protein biomaterials can be generated by genetic engineering of resilin-encoding genes. Exon 1 from resilin is critical for its resilience properties. The recombinant protein made from Exon 1 encoding the N-terminal domain in native resilin as cloned and expressed is a 30 KD soluble protein in ***Escherichia Coli*** which exhibited resilience closer to original resilin [13]. This sample had up to 92% resilience and could be stretched to over 300% of its original length before breaking [14]. A full-length recombination protein of Exons 1, 2 and 3 also exhibited elastic properties closer to the Partial clone. r-Resilin can be stretched more than twice their original length and recover more than 90% of the deformation energy once stretching force is removed [15]. Resilin is mainly unstructured and forms terms as well as more extended structures [16]. The polymers displayed adhesive properties.

Applications of Resilin

- Resilin is a protein of high elastomeric property having about 97% efficiency in energy conversion.
- It has to last for the lifetime of the insect and hence cannot degrade but may get modified as per the insect adaptations.
- It does not undergo tearing or fatigue even under stress conditions except in foraging insects where it gets damaged.
- It has greater elasticity than rubber and is easy to produce under natural conditions. Hence, it is the best possible substitute for rubber.
- Both neurogenic and myogenic insects have resilin at the fulcrum causing low or high wingbeat frequency.
- The mechanical and biological properties of resilin can be readjusted by using protein engineering including synthetic muscles, vocal cords, cardio-vascular, semi-lunar valves and soft cartilage.

Thus resilin has great importance in biological industry and biomedical applications.

Silk

Silk is an important raw material for textiles and other goods with unique properties as a natural fibre. The term silk in general is applicable to threads spun by certain caterpillars, spiders and mussels. It plays an important role in protein chemistry,

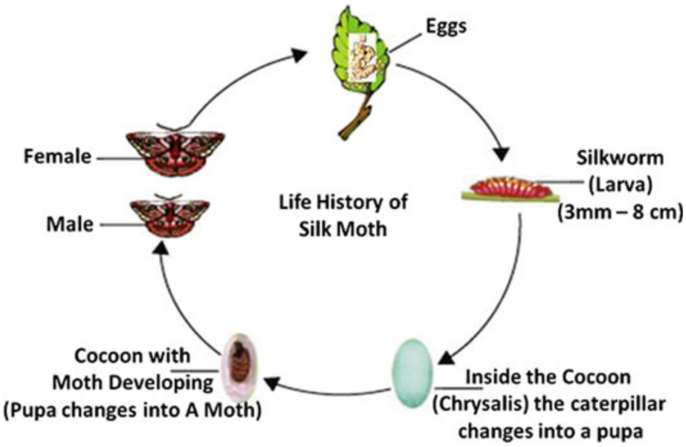


Fig. 8.4 Life history of silk moth, ***Bombyx mori*** (L) (Metamorphosis)

genetics and genetic engineering. The present article reviews the information on silk from [17] and [18].

It is a natural fibre secreted by the silkworm. The larvae of silkworm secrete the true silk. ***Bombyx mori*** is the most common domesticated silkworm. It belongs to the small family known as Bombycidae. The adult moths are robust. The caterpillar larvae are rough, wrinkled, naked, white and with a projection on the opposite side. The larvae feed on large quantities of mulberry leaves and spin silk cocoons. Silk production and trade are more common in China, India, Japan and some parts of Europe.

The life cycle (metamorphosis) involves four stages: Egg, Larva (silkworm caterpillars), Pupa and Adult Moth (Fig. 8.4).

Structure and Properties of the Silk Fibres

The silk is secreted by silk glands consisting of two long tubes of variable thickness present in the body of the caterpillar. Each gland has three parts and they are (i) anterior (ii) middle and (iii) posterior parts.

Silk fibre consists of 75–83% of fibroin and cementing material sericin ranges from 17 to 25% depending on various factors. Fibroin and sericin are the two major proteins involved in the formation of silk thread (Table 8.1).

Fibroin is made up of 16 amino acids, and raw silk is composed of two filaments that are produced by fibroin. These two filaments are generally cemented together by a gum-like substance which is known as sericin, which involves different types of mineral salts, fat and wax.

Table 8.1 Average chemical composition of raw silk fibre

Content	Percent
Fibroin	75
Ash of silk fibroin	0.5
Sericin	22.5
Fat and wax	1.5
Mineral salts	0.5

Table 8.2 Commercially exploited sericigenous insects of the world and their food plants

S. no	Common name	Scientific name	Origin	Food plant
1	Mulberry Silkworm	*Bombyx mori*	China	*Morus indica* *M. alba* *M. multicaulis* *M. bombycis*
2	Tropical Tasar Silkworm	*Antheraea mylitta*	India	*Shorea robusta* *Terminalia tomentosa* *T. arjuna*
3	Oak Tasar Silkworm	*Antheraea proylei*	India	*Quercus incana* *Q. serrata* *Q. himalayana* *Q. leuco tricophora* *Q. seicarpifolia* *Q. grifithi*
4	Oak Tasar Silkworm	*Antheraea frithi*	India	*Q. dealdata*
5	Oak Tasar Silkworm	*Antheraea compta*	India	*Q. dealdata*
6	Oak Tasar Silkworm	*Antheraea pernyi*	China	*Q. dendas*
7	Oak Tasar Silkworm	*Antheraea yamamai*	Japan	*Q. acutissima*
8	Muga Silkworm	*Antheraea assamensis*	India	*Litsea polyantha* *L. citrate* *Machilus bombycine*
9	Eri Silkworm	*Philosamia ricini*	India	*Ricinus communis* *Manihot utilisma* *Evodia fragrance*

Raw silk is further treated to remove gummy materials along with other impurity types by using Scouring Process. The silk fibre produced will be applied for different products and fabrications (Table 8.2).

Texture of Silk Thread

The raw silk threads have a slight lengthwise striation. It is made up of two fibrion filaments cemented in so-called silk gum or sericin. The detailed structure of fibroin filament consisting of fibrils, microfibrils and polymer molecules is rather notable [17, 18].

About Sericulture

Sericulture is the term, which denotes the production of silk through silkworm rearing commercially. Sericulture is a labour-intensive agro-industry ideally suited for rural areas. Sericulture provides an excellent and unique opportunity for socioeconomic development and employment in developing countries like India. Historical evidence shows that silk was discovered in China and that the industry spread from there to other parts of the world. Geographically, Asia is the main producer of silk in the world and produces over 95% of the total global output. Though there are over 40 countries on the world map of silk, the bulk of it is produced in China and India.

Chemical Composition and Properties

The percentages of fibroin and sericin have been shown in Table 8.1. Glycine, alanine, serine and tyrosine contribute to 90% of fibroin molecules. Sericin binds the fibroin filaments and has a protein structure having similar to rubber elastic properties.

Mulberry silk has good elastic properties and it is also hydroscopic. It also exhibits anisotropy and has high electrical resistance. It is unaffected by temperature up to 140 °C. Silk can be dyed with all kinds of dyes as used in the case of wool. Silk has a wide range of applications in textiles, protein chemistry, genetics and also in genetic engineering. Minimum numbers of allergies have been reported in the medical literature. It is a natural fibre which can be compared with any synthetic fibre and the product has its uses in industry, medicine and parachuting.

Physico-Chemical and Mechanical Properties of Silk

The solubility of spider silk is based on its hydrophilic nature. The density of spider silk is about 1.4 gm/cm^3 and on the other hand that of steel is 7.8 gm/cm^3. Spider silk has very good tensile strength and exhibits torsional resistance. The silk is highly elastic, i.e. to the extent of 300%. It can withstand the impact of the weight of a honey bee weighing 200 mg flying with a velocity of 3 m/s. This character as a predator helps in catching and eating the insects.

Genetic Engineering

There is a lot of variation in the mechanical and physiological properties of silk as produced by various spiders. Most of these fibres share a common primary structural pattern with the large central core of repetitive domains for mechanical strength flanked by a non-repetitive N and C terminal domain helping in the fibre formation during spinning. Dragline silk proteins were given much emphasis for the production of recombinant silk which differ in the percentage of proline residues. Some of the silk proteins like MaSp1, MaSp2 and AcSp1 from different sources of Nephella clavipes, Araneus Diadematus, Arglope and Trifasciata were cloned in different organisms like *E. Coli*, Salmonella, Yeast, etc. with recombinant protein product yields ranging from 40 to 300 mg/L. It has not been possible to breed spiders in the laboratory even today. Hence, it is advisable to produce spider silk by DNA technology [19].

Summary

In this chapter, chitin composition and its applications have been discussed in some detail. The role of resilin in insect flight and in the jumping process has been stressed. Silk as a natural fibre thread giving details of its structure and compositions has been mentioned. A mathematical approach has been attempted to understand the elastic nature, energy stored or consumed and force exerted during its action in the resilin. However, the availability of this fibre in the required quantity is a major problem.

The most significant aspect of spider silk is its strength and its bulletproof nature. Hence, it is being used in the defence industry for making bulletproof jackets of soldiers. A summarized comparison between spider and tasar silk moth from various sources has been listed in Table 8.3.

Table 8.3 Comparison between Spider and Tasar Silk Moth (from various sources)

<table>
<tr><th>S. no</th><th>Details</th><th>Spider</th><th colspan="3">Silkmoth</th></tr>
<tr><td>1</td><td>Class
Order</td><td>Arachnida
Araneae</td><td colspan="3">Insecta
Lepidoptera</td></tr>
<tr><td>2</td><td>Body segments</td><td>Cephalothorax
Abdomen</td><td colspan="3">Head
Thorax
Abdomen</td></tr>
<tr><td>3</td><td>Antennae</td><td>Absent</td><td colspan="3">Present</td></tr>
<tr><td rowspan="4">4</td><td rowspan="4">Wings and Wing venation</td><td rowspan="4">Absent</td><td>Parameter</td><td>Male</td><td>Female</td></tr>
<tr><td>Wingspan</td><td>16 cm</td><td>18 cm</td></tr>
<tr><td>Fore wing area</td><td>2121 mm^2</td><td>2350 mm^2</td></tr>
<tr><td>Hind wing area</td><td>1584 cm^2</td><td>1850 cm^2</td></tr>
<tr><td>5</td><td>Legs</td><td>Four pairs of legs and each leg is composed of five segments</td><td colspan="3">Three pairs of thoracic legs and each leg is composed of five segments</td></tr>
<tr><td>6</td><td>Eyes</td><td>Four pairs on the top front area of the cephalothorax
Ocelli are present</td><td colspan="3">A pair of compound eyes on either side of the head
Ocelli are absent</td></tr>
<tr><td>7</td><td>Silk characters</td><td>1. Strength—silk's tensile strength is comparable to that of high-grade alloy steel (450–1970 Mpa)
2. Silks stretch up to five times to their relaxed length without breaking
3. Toughness—dragline silks have a very high toughness which equals that of commercial filaments
4. Temperature—dragline silks can hold their strength below −40 °C (−104 °F) and upto 220 °C (428 °F)
5. Super contraction—when exposed to water, dragline silks undergo super contraction, shrinking up to 50% in length and behaving like a weak rubber
6. Spider silk—average maximum breaking stress (MPa) ranges from 710 to 1850
7. The primary structure is its amino acid sequence, mainly consisting of highly repetitive glycine and alanine blocks. On a secondary structure level, the short side-chained alanine is mainly found in the crystalline domains (beta sheets) of the nanofibril, and glycine is mostly found in the so-called amorphous matrix</td><td colspan="3">1. Elasticity is moderate to poor
2. Silkworm silk, therefore, has a linear density of approximately 1 den
3. Silk is very elastic. It can stretch 10–20% without breaking
4. Silk is resistant to most mineral acids, except for sulphuric acid
5. Silkworms were genetically altered to express spider proteins and fibres measured average maximum
6. Fibroin is made up of the amino acids Gly-Ser-Gly-Ala-Gly-Ala and forms beta-pleated sheets. Hydrogen bonds form between chains, and side chains form above and below the plane of the hydrogen bond network. The high proportion (50%) of glycine allows the right packing. The addition of alanine and serine makes the fibres strong and resistant</td></tr>
</table>

(continued)

Table 8.3 (continued)

S. no	Details	Spider	Silkmoth
8	Uses	1. Vitamin K 2. As a thread for crosshairs in optical instruments such as telescopes and microscopes 3. In 2011, spider silk fibres were used in the field of optics to generate very fine diffraction patterns	1. Used for industrial and commercial purposes, such as in parachutes, bicycle tires, comforter filling and artillery gunpowder bags 2. After removal of outer irritant sericin coating of the silk, it is suitable as non-absorbable surgical sutures

Note Spider and spider fibres have been included from comparing with insect silk; however, insects and spiders belong to the same phylum Arthropoda

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Chapter 9
Aeroelasticity

N. Chari, Prasad Mukkavilli, A. G. Sarwade, and Kamalakar Pallela

Abstract Aeroelasticity is a branch of physics and engineering dealing with interaction between inertial elastic and aerodynamic forces. When a semi elastic body is exposed to a fluid flow (Collar's diagram) it develops fluid dynamic forces. Aeroelasticity includes static aeroelasticity (steady state) and dynamic aeroelasticity (fluttering and buffeting). Low and high wing beat frequencies are observed in the insect flight. Our knowledge of aeroelasticity in the insect flight is in the initial stage. There is a need to do further serious nano material research for proper prediction of loads and vibrations characteristics in flapping wings and MAVs.

Keywords Aeroelasticity · Static and dynamic aeroelasticity · Fluttering · Buffeting · Low *Re*

Introduction

Aeroelasticity is a branch of physics and engineering dealing with interactions between inertial, elastic and aerodynamic forces when a semi-elastic body is exposed to a fluid flow (See Fig. 9.1). It has great applications in the aeronautical industry, structural engineering, bio-aerodynamics and power transmission lines. This study can be broadly classified as static and dynamic aeroelasticity (vibrational response).

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Fig. 9.1 Collars diagram (Δ)

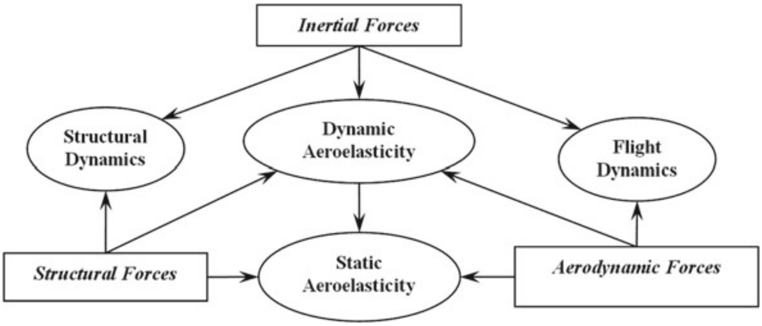


Fig. 9.2 Schematic representation of aeroelasticity

The body of a biological flier is semi-elastic in nature. During the flight, they are subjected to inertial, aerodynamic and elastic forces. The wing motion may also include translation, rotation, oscillation, twist, flapping or a combination of some of these modes. The study of *Structural Dynamics* includes the interaction between structural forces and inertial forces. This study also involves motion and related stresses in static and dynamic conditions. Considering a rigid solid body moving in a fluid medium or a fluid flows over a rigid body, the relative motion results in aerodynamic forces. It also includes frictional and viscous forces by the virtue of mass, inertia, velocity and acceleration effects. Hence, all these studies come under the purview of Flight Dynamics.

Static Aeroelasticity deals with the interaction between the structural forces in terms of stress, strain and elasticity effects with the aerodynamic and viscous forces.

Dynamic Aeroelasticity on the other hand includes the following aspects:

1. Simultaneous interaction among the inertial and related forces of the body.

2. Structural deformations resulting due to the semi-elastic nature of the body (wing) leading to the development of aerodynamic forces.
3. The viscous effects of the fluid flow as it flows over the body.
4. Boundary layer separations.
5. The formations of the vortices and the associated lift, drag and thrust forces.

The subject of Aeroelasticity considers all aspects of the material, inertial and structural interactions of an elastic body moving in a fluid stream.

The birds, insects and bats are natural fliers in contrast to man-made fliers such as aeroplanes, missiles, helicopters, UAVs and MAVs. The natural fliers are capable of flying in various environmental conditions such as gusts, heavy rains and may be even in storms. They have cultivated the art of flying including forward flight, hovering and various forms of gliding. In this process, the natural fliers can perform various body and wing movements because they have relatively flexible bodies and wings. The flapping of the wings in these natural fliers is considered to be a complex motion, which includes sidewise, up and down as well as bending/twisting motions. This can, in a way, be compared to the swimming carried out by aquatic animals. All such actions of these natural fliers are possible due to the semi-elastic nature of the wings, body and the fulcrum, associated with their structural deformations. On the other hand, man-made fliers such as aeroplanes and helicopters using fixed or rotor wings for their flight have limited capabilities and flexibility in wing movement.

Historical Background

In 1896, Samuel Langley was the first to design a flying bi-plane aircraft planned to be launched by Catapult Mechanism. However, as soon as it took off, it had an accident due to the twisting of the wings, and later on, it was attributed to aeroelastic interactions. In 1903, Wright Brothers were able to fly another bi-plane at 30 mph. This machine had light wings, a powered engine and two propellers. In 1905, they built an improved aeroplane and flew a distance of twenty-four miles in thirty-eight minutes. From 1930 onwards, only the monoplanes are flying and are popular as compared to the bi-planes (A type of aeroplane having two sets of wings, one above the other, where there is a lot of interference).

A definition for aeroelasticity is given by Arthur Roderick Collar in 1978 as "*the study of the mutual interactions that take place within the triangle of the inertial, elastic, and aerodynamic forces acting on structural members exposed to an airstream, and the influence of this study on design*" [1].

Importance of Aeroelasticity

Aeroelasticity plays an important role in the transonic, supersonic and hypersonic flights in addition to subsonic flight. The application of aeroelasticity concepts to insect, bird and bat flight remains to be elucidated in detail. In the early days, aeroelasticity was almost ignored during the process of flight designs. However, many accidents were attributed due to aeroelastic problems in various fields of study. Gas turbines, rotor wings of helicopters, long bridges, transmission lines, ships and offshore structures, very tall buildings and biological phenomena involving cardiac failures and bio-aerodynamic accidents come under this category. A large number of structural failures in man-made fliers such as blade and wing flutter, buffeting and uncontrolled structural vibrations causing excessive fatigue forced the scientists to attempt a deeper study and understanding of the subject of Aeroelasticity. A lot of information about aeroelasticity is available in standard textbooks and the following sections are mostly reviewed from [2]. Structures such as wings, aerofoils, chimneys and bridges are exposed to aerodynamic forces. Blunt shapes create a continuous stream of vortices. Bridges are destroyed by aeroelastic fluttering.

Static Aeroelasticity

Static aeroelasticity deals with the static response of an elastic body moving in a fluid flow. These aeroelastic effects cause typically divergence and control reversal phenomena.

1. In **divergence**, there is a sudden elastic twist of the wing due to resistance to overcome deformation.
2. In **control reversal**, the ailerons and control surface functions get reversed due to deformations and may lead to the opposite effect.

Divergence

The uncoupled torsional equation for motion is given by

$$GJ\frac{d^2\theta}{dy^2} = M' \tag{9.1}$$

where y is spanwise dimension and θ is the elastic twist of the beam in radians.

For some special boundary conditions where an airfoil is tested in a wind tunnel, it is possible to eliminate the phenomenon of divergence (Hodges and Pierce 2002).

Control Reversal

It is a loss due to the deformation of the main lifting surface, which is also considered to be an expected response of a control surface. Generally, control reversal speeds are derived analytically according to torsional divergence. In some aerodynamic applications, control reversal can be used as an advantage and forms some part of the Kaman Servo-Flap Rotor design. Servo flap is a small airfoil located at about 75% span of the rotor blade, situated on the trailing edge of each rotor blade. Their function is similar to that of an elevator on fixed-wing aeroplanes. The control reversal can be used to aerodynamic advantage (Kana-Servo-flap rotator design).

This problem of control reversal with flexible wings of a high aspect ratio seems to be an important area of study. With a high aspect ratio, the performance and flight speeds tend to increase while compared with low aspect ratio wings. However, in modern aircrafts with flexible wings at very high speeds, additional elastic deformations are introduced in the wing structure, which influences spanwise aerodynamic load distribution [3]. This in turn affects the aerodynamic performance of the flier.

The study of control reversal and torsional divergence speed as discussed above is helpful to design a prescribed flight envelope that helps for a safe flight with a guarantee. There are many engineering tools available to analyse control surface reversal such as non-linear multi-body dynamic analysis, DYMORE, cross-sectional analysis, two-cell analysis, VABS and two-dimensional aerodynamic coefficient analysis [3].

Dynamic Aeroelasticity

This is due to the interactions between all the three forces shown in the Collar Diagram (Fig. 9.1). The interaction between the inertial and elastic forces causes structural vibrations. Typical examples of dynamic aeroelasticity are flutter and buffeting.

Flutter

It is a dynamic instability of an elastic structure in a fluid flow. This is caused by a positive feedback mechanism between the deflection of the body and the fluid flow, as it happens in the functioning of heart valves at low frequencies. Such flutter is typically noticed in the functioning of heart valves in higher animals because of the interaction of the blood flow with semi-elastic heart valves. The action of the heart and its components are controlled by the Sino-Auricular node. Atria beat faster than ventricles. Atrial flutter is a type of common abnormal heart rate rhythm similar to atrial fibrillation. This is the most common abnormal heart rhythm. It is a kind of rapid heartbeat supra-ventricular tachycardia. The flutter can be explained through a linear oscillator system executing Simple Harmonic Motion (SHM) and can be thought of as a self-induced vibration with practically very little damping effect. In soft flutter, the net damping decreases gradually up to the flutter point. For non-linear systems, flutter action acts as a Limit Cycle Oscillation (LCO). The fundamental frequency is influenced by the length, size and tension of the vocal cords. This frequency in adults averages about 25 Hz (males) and 210 Hz (females). Young insects (imago), young birds and young bats also exhibit wing flutter before attaining full flight. Flutter means to move or flap the wings quickly without being able to fly. Flutter is common in aviation, aeronautics, medicine and electronics. Flutter can be of hard and soft type.

Buffeting

Buffeting is a high-frequency instability caused by an increase in load. Buffeting is usually observed in fast-flying aircraft. It is a high-frequency phenomenon where instability is caused due to shock waves resulting from high-speed supersonic flow past the body. It is a random forced vibration, which also influences the tail unit of the aircraft structure resulting in unexpected vibrations, damage and stall. Buffeting means irregular oscillations of an aircraft, due to turbulence leading to high-frequency instability, leading and stalling. Some of the methods suggested for buffet detection are as follows:

1. Pressure coefficient diagram.
2. Pressure divergence at the trailing edge.
3. Computing separations from trailing edge based on the Mach number.
4. Normal force fluctuating divergence.

The model suggested can be used to predict the flutter margin.

The Mach number is defined as the ratio of the velocity of the flier to the local speed of sound. Mach numbers for insects are very low. As the flying object is in the transonic range of Mach numbers, moving shock waves dominate the flow and the intensity of the shock waves affects the stability of the flier. This situation will not arise in the case of insect flier where the Mach numbers are well within the subsonic range and M is less than 0.3. However, the Mach number in high-speed fliers varies from 1.3 to 25. Aeroelastic effects can persist in such low subsonic flow regimes because of the elastic nature of structural deformation as in the case of flexible flapping wings of low- and high-frequency fliers (Neurogenic and myogenic).

Aeroelasticity involves the study of structural damping, inertia and mass characteristics of the flying objects besides the external aerodynamic loads and their dynamic nature. A proper estimation of these loads and vibration characteristics could help in the design optimization of MAVs as well as the flapping wings. The model should preferably include details of the interacting aerodynamic forces and the way their dynamic vibrations act in relation to flight surfaces. These models can be helpful in predicting the flutter margin and potential problems leading to stall. Irregular oscillations on the part of an aircraft cause buffeting.

The study of aeroelasticity assumes greater importance in relation to insect flight as they have semi-elastic thorax, elastic resilin and membranous flexible flapping wings made up of chitin, which is a polysaccharide amine. Even the contracting muscle is also elastic in nature. Although knowledge of the insect bio-aerodynamics helps in a systematic understanding of insect flight and acts as a guide in the design of MAVs. However, it may not be possible to bio-mimic a natural flier in totality since it represents a highly complex type and our understanding of natural objects and their functioning is quite inadequate for the design.

Transonic Aeroelasticity covers a transonic range of high Mach numbers, where a moving shock wave dominates the flow. The intensity of the shock affects the stability of the flier and this is known as a transonic dip.

Dynamic Response

Dynamic Response is analogous to aero-servo elasticity. In biological flight response to gust/ landing is almost instantaneous and more accurate as compared to that of the man-made aerial vehicles because of fast feedback systems due to sensory organs prevalent in the biological fliers involving the brain.

Aeroelasticity in Insect Flight

Extensive wingbeat frequency studies were performed on a wide range of insects by the author and his team at Kakatiya University, Warangal, and at SNIST, Hyderabad. The natural wingbeat frequency of ***T. javanica*** was found to be 50 Hz. Further experiments showed that.

1. The frequency increases with a reduction in wing area (mutilation).
2. It progressively decreases through wing loading with the addition of loads at the wing tip.
3. Resilin at wing base contributes to aeroelasticity in neurogenic and myogenic fliers.
4. This is also true for ***C. purpureous*** which has a frequency of about 100 Hz.

The frequencies were measured by a stroboscope and confirmed by Mass Flow Theory. The above method of loading or unloading the wings can possibly be adapted to decrease or increase the natural frequency of the MAV [4].

Non-dimensional Parameters of Insect Flight

Shyy et al. [5] gave a comprehensive literature survey of insect flight research for MAV development and problem areas to be tackled. Some of the important features highlighted by Shyy et al. are considered as guidelines for the design of MAVs are as follows:

Non-dimensional Numbers (Relevant to Scaling Laws).

a. **Reynolds Number (Re)** is the ratio of inertial forces to viscous forces.

$$Re = \frac{\rho B_{eff} U_{erf}}{\mu} \tag{9.2}$$

where ρ is Air Density.

B_{eff} is the Mean chord length of the wing for insect flight study.
U_{ref} is Free stream velocity.

In hovering flight,

U_{ref} is the mean wing tip velocity that is the angular velocity.
θ is full stroke amplitude (radians) for flapping.

$$w = 2\pi f$$

where $f = \frac{1}{T}$.
l is wing span semi span; T is time for one cycle of flapping;
f is the wingbeat frequency.

b. Reduced Frequency.

$$K = \frac{\pi f c_m}{U_{ref}} \tag{9.3}$$

c_m is mean chord length of the wing.
f is frequency.

iii. Strouhal Number (St).

$$Strouhal\ Number = \frac{2fh_a}{U_{ref}} = \frac{wing\ tip\ velocity}{U_{ref}} \tag{9.4}$$

where

f is the flapping frequency,

h_a is the flapping amplitude,
U_{ref} is the free stream velocity or forward velocity of the body.

The Strouhal number describes the wing kinematics and defines the ratio of local inertial forces that are due to unsteadiness of the flow to convective inertial forces that are due to the changes in velocity from point to point in the flow field. *St* is an important parameter in the study of unsteady oscillating flows.

Salient Features of Aeroelastic Phenomena in Insect Flight

- Insect wings are anisotropic due to their membranous structure and longitudinal vein configurations. Major veins run along the wing span. The spanwise bending stiffness is 1 to 2 orders larger than the chordwise bending stiffness and spanwise stiffness is proportional to (where C^3 is chord length) whereas the chordwise stiffness is proportional to C^2.
- All insect wings have a reinforced leading edge. Some insects have (ex. Dragon Fly) corrugated planforms at the leading edge. This helps in preventing fatigue fracture and enhances the flexibility and warping rigidity.
- The process of achieving flight stability and the influences of non-linearities/anisotropy on wing aerodynamics are still not clear and hence need further investigations.
- The insect flight in the low Re regime (10^1 to 10^4) with respect to flow physics remains to be elucidated fully.
- *Pronation and Supination*: At the end of the upstroke, the wings pitch up. This is Pronation. Supination is at the end of downstroke when the wings pitch down. These are more or less twisting/ untwisting movements at the wing base and have aeroelastic implications. The elastic nature of resilin has been discussed in detail in Chap. 7.
- In general, it is observed that in a flapping wing, the structural elastic forces are predominant as compared to the aerodynamic forces.
- The elastic camber generated by the wing flexibility enhances the lift and thrust forces.

Rigid, Flexible and Very Flexible Wings

Experimental work on wings made of steel sheets has been explained. The sheet thicknesses were 3.81 mm, 0.127 mm and 0.05 mm, respectively, for the rigid, flexible and very flexible wings. The flexible wings contribute to the enhanced lift [5].

- 2-D versus 3-D, CFD studies: To reduce the computation time, quite often 2-D studies were done. But in some cases, there can be a marked difference between the 2-D and 3-D analyses.

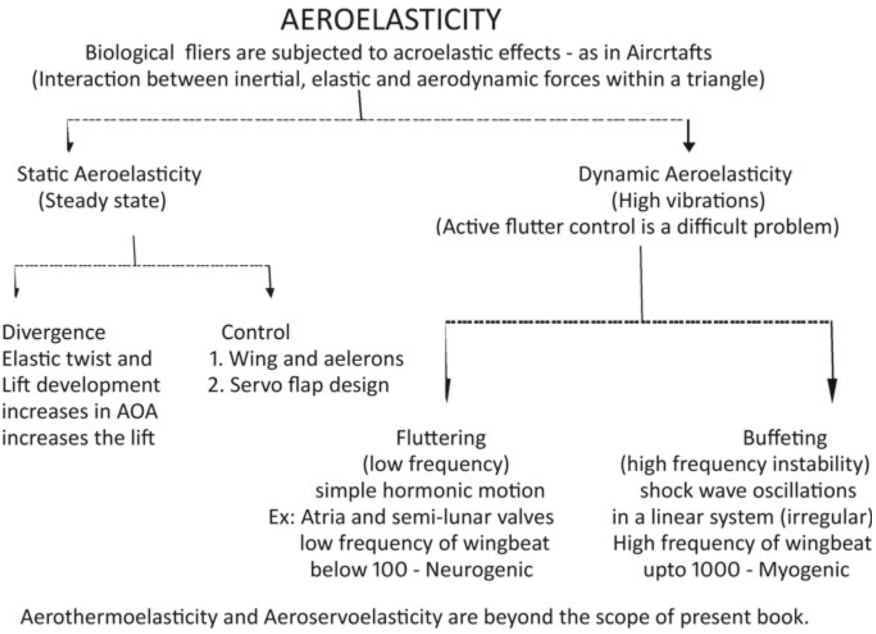
- Wing Kinematics: This is dependent on the wing structure and degrees of freedom. In nature, the insect wing structure is membranous with veins running longitudinally.
- Optimizing for Higher Lift: Both the lift and drag forces increase with frequency. The maximum lift is found with added rotation. The pitching angle amplitude of 35°–45° was found to be optimum, with a phase angle of 90° between pitch and plunge (using 2-D solver). This was found by multi-objective optimization. Wings with corrugated leading edges sometimes produce a higher lift as in the case of dragonflies.
- The pitching axis nearer to the centre of the wing in the chordwise direction exploits the vortices shed from both the leading and trailing edges [6]. They observed that lift and drag increased with an increase in flapping frequency, stroke amplitude and the advanced wing rotation.
- The unsteady flapping aerodynamics results in the enhanced lift due to the following mechanisms as described in Chap. 2 and listed below:

  – Clap and Fling.
  – Rapid pitch up rotation (analogous to Magnus Effect during the stroke reversals).
  – Wake capture (Wing-Wake Reaction).
  – Delayed Stall of Leading Edge Vortices.
  – Tip Vortex.
  – Passive Pitching Mechanism, i.e. the wing torsional flexibility causing pitching motion.

Summary

Aeroelasticity involves the structural damping and mass characteristics of the flier object besides the external aerodynamic loads and their dynamic nature. A proper prediction of these loads and the vibration characteristics help in the optimization of both the MAV body as well as the flapping wings. The model should preferably include details of the interacting aerodynamic forces and the way they vary. These models can be helpful in predicting the flutter margin and any other problems involving the initiation of the stall.

The aeroelastic phenomena in general are found to be beneficial for the design of insect mimicking MAVs. To the extent possible, the natural materials for the membrane and the resilin, supporting the wing at the fulcrum, can be used in their design. Resilin is reported to be highly elastic. There is a need to do further studies on the insects like ***T. javanica***, ***C. purpureous*** and Cicada where considerable experimental data exists. If it is not feasible to use the natural materials for the MAVs, then the experimental studies are to be done on the MAV configurations with substitute synthetic materials like Mylar, to study their aeroelastic effects and fatigue resistance at the low Re numbers [4].



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Chapter 10
Insect Migration

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Abstract Insect migration as compared to migration in homeotherms is characterised by low mass, body offering less drag, chitinous membranous wings in pterothorax, average frequency of wingbeat and unique type of sense organs for orientation and navigation. The migrating insects have powerful aerobic flight muscles and elastomere resilin at the wing base. Best examples of migratory insects are ***S.gregaria***, Monarch butterfly, and Dragon flies. The migration of desert locust from Africa to India and remigration is a notable feature. Similarly Monarch butterflies migrate from Canada to Mexico and vice versa covering a distance of 4000 km. Return journey is carried by subsequent generations involving metamorphosis. A table has been given explaining general aspects of migration.

Keywords Nocturnal migration · Visual land marks · Optical flow · Endurance · Low *Re* · Wing speed · Biomimicry

Introduction

It is interesting to note that insects, birds and bats evolved about 350, 250 and 50 million years ago respectively and so migration has evolved independently in these three phylogenitically groups of different fliers. Migration is a kind of seasonal practice for the biological fliers and a general adaptation for adverse environmental circumstances as migrants move between discrete locations. Migration is an aerial

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adaptation for dispersal mechanisms. Some biological fliers such as insects, birds and bats migrate depending on pronounced flight activity in search of food, sexual activity (breeding grounds) and as an adaptation for favorable environmental conditions. Migration can broadly be classified as short distance and long distance, depending upon the species flying capability. During migration, the flier needs continuous supply of energy (fuel). The flier needs proper orientation by making use of its sensory feedback systems which are extremely complex and subsequently it has to orient and fly in the direction of its destination.

Insect Migration

Insect migration is characterized by relatively low mass, body offering less drag, chitinous membranous wings on thorax, high frequency of wing beat and extremely well developed unique sense organs for navigation different from homeotherms. Insects are equipped with well developed mouth parts, compound eyes, ocelli (simple eyes) and a pair of sensory antennae, sensory hair with innervations at the base known as trichobothria which are present on body and wings. They help in detecting wind flow. The migrating insects possess better and efficient aerodynamic features, well developed powerful aerobic flight muscles and an elastic rubber like substance known as resilin at the wing base. The resilin and wing get coupled and contribute for low and high frequency wing movements in neurogenic and myogenic fliers and for the development of aerodynamic forces due to beating of flapping flexible wings. The migration is possible due to reaction between sensory organs and various navigation factors which is not fully understood. Many insects migrate in swarms. The best example of migrating insects are migratory locust and American monarch butterfly which migrate a distance of more than 4000 km. In many cases return migration (home coming) is done by subsequent generation of fliers as in the case of locusts and Monarch butterfly. On the other hand return migration in homeotherms, same flier flies along with young ones.

Migratory insects cover a distance ranging from a few kilometres to some thousands of kilometres based on different atmospheric weather and geographic conditions [1]. Desert locust ***Schistocerca gregaria*** recorded to be having the longest migration is mostly found in Caribbean islands and at some regions of Panama Canal, Africa, Middle East, Arabia and India. They flew in some kinds of tropical wave patterns for a distance of 4,500 km [2]. Swarms of *Schistocerca* involve about 1,000,000,000 locusts. The swarms cover a distance of 30–40 km per day. The swarms are also called as startiform and cumuliform swarms [3]. The migration of ***S.gregaria*** from Africa to India and also remigration has been shown in Fig. 10.1. The directed long migration in locusts is controlled by winds, and it is tenacious.

Many entomologists and scientists have noted that most of the insects do migrate at high altitudes by using fast flowing airstreams to travel long distances. Wind streams influence insect flight strongly during migration [1]. Strong uni-modal distribution of

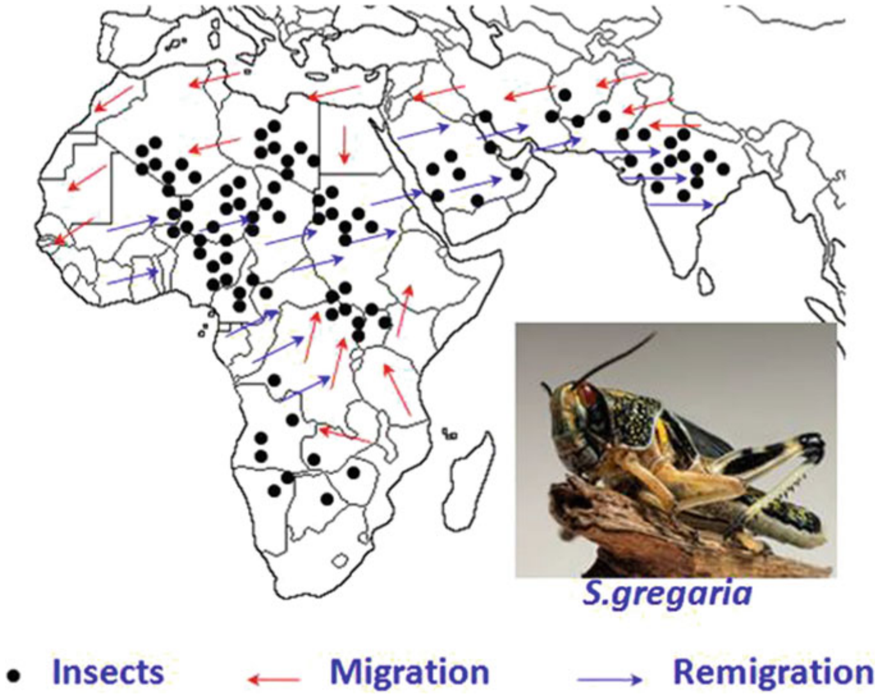

Fig. 10.1 Migration of *S.gregaria*

flight heading is exhibited by Nocturnal fliers. Sometimes these insects get concentrated into shallow altitudinal zones. The atmospheric turbulence is another important factor to be considered seriously for long distance migrations in insect flight towards downwind direction [4].

Recently, Chemical signal(s) of Pheromone for migratory locusts as 4-VA (Vinylan-isale) have been reported which induce swarming in solitary locusts says Prof. Le Kang, Chinese Academy of Science, Institute of Zoology. This chemical is released by hind legs, and the odor is detected by the antennae of other locusts. Swarms can include billions of locusts and cover hundreds of square miles.

The presence of 4-VA has to established and suitable mild pesticides maybe suggested so that Human Health and Crop problems can be attended. The 4-VA secretion which induces swarming behavior has to be prevented by using suitable chemical. 4-VA needs further research (Deccan Chronicle Report 14th August 2020).

Definition for Insect Migration

Mere movement does not mean to be migration. Vegetative behaviours like feeding and reproduction process in insects will be suppressed temporarily during the course of migration [5].

The migration of insects can be classified based on specific behaviour phases as follows [6]:

- Insects migrate with a *determined mission* to move from one place to other favorable place.
- Some insects will move consistently in a *straight movement*.
- Some insects focus on moving to one targeted area without halting at suitable host plants.
- In the process of preparation a few insects will undergo with *distinctive changes* in behavior for reproduction. Insects like locusts initially are solitary will become gregarious during migration. They also store lot of fat content as a fuel for migratory flight. Insect body fat plays a major role in migration for releasing energy by using triglycerides.

Kennedy [7] explains a limited criterion for defining migration as for a behaviour persistent.

Evidence for Insect Migration

Some of the important observations are listed below [8].

- Large numbers of insects from different insect orders flying in one direction with steady air flow were observed by field naturalists.
- Sudden appearance/disappearance of insects with wings in large numbers which were not observed previously is interesting.
- Many insects were usually seen flying at far off oceanic islands and at high altitudes.

The first insect mass migration of over 10,000 moths was reported to be monitored by radars oriented directly with downwind [5].

Reasons for Migration

There are many reasons for insect migration, and these may include physiological and ecological as well. Some of the critical reasons for migration are listed below [9]:

- The locomotory functions are enhanced, and vegetative functions (like feeding and reproduction) are suppressed.
- Migration takes place before reproduction in the life of an adult insect.
- The insects with migration ability tend to have temporary habits and have high potential to increase their population.
- Physiological and ecological parameters of migration are bound to change.

Desert Locust completely depends on seasonal rains for breeding. However, based on climatic conditions they migrate to different areas. Considering the availability of food, these insects will migrate and the rate of migration increases to a particular area in the process of searching for food [10]. The female insects prefer to migrate from breeding area to feeding area. These insects develop mature ovaries and will return to the place from where they came or to a similar region for laying eggs. Such migration involves longer distances with unusual long life spans including diapause [11]. Migration itself is a highly complex problem due to diapause.

This climate during hibernation will not be suitable for breeding and hence the insects return to the same place for laying eggs. Such migration process involves longer distances. During spring again they return to breeding areas. A ladybug (*Hippodamia convergens*) lives in California to hatch eggs and adults develop in spring. During summer they migrate to suitable mountains for laying eggs [11].

Cardé [5] reported a special mechanism in moths in order to determine the direction of displacement during airborne flight. They presumably descend to the ground levels if the wind direction is wrong during night times and stop migration.

Monarch butterfly (*Danausplexippus*) is known to be the best example for return migration. In autumn, these butterflies migrate to southward (see Fig. 10.2) for hibernating by travelling 3,600 km and migrate back towards north for breeding during

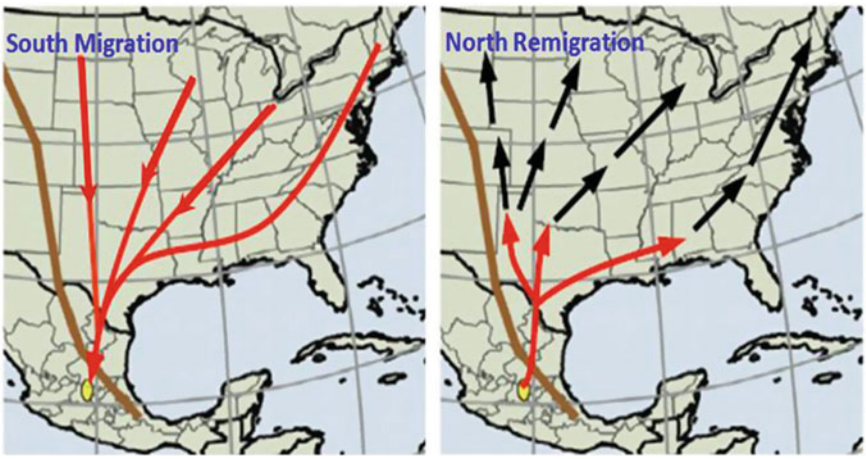

Fig. 10.2 Migration cycle of Monarch butterfly in North America. *Source* Guerra and Reppert [12] (Modified Diagram)

spring. Some of the butterflies in this group will be the members of first generation, capable of travelling 130 km in a day. Monarchs use polarized skylight pattern for navigation. The day length decreases for migration towards south and day length increases during the movement towards north [11, 12]. Kuester et al. [13] reported the migration of boll weevil depending upon population genetic strategies.

Johnston [14] on Bumblebees discussed the new record by flying at a high altitude of about 9000 m above the height of Himalayas (8,848 m). Generally, bumblebees are considered to be the finest flyers, even at low pressures on high altitudes (i.e., death zones above 8,000 m) they are able to fly with low muscle temperatures and are maintaining a thoracic temperature of 44 °C even at that height. Locust has been reported to migrate at a height of 6000 ft at a very low temperature range up to −30 °C (Table 10.1).

Table 10.1 Variation of atmospheric pressure, density and temperature with altitude

S No	Geometric height, h M	Pressure, p Pa	Density, ρ kg/m^3	Temp T K
1	−250	104,365	1.2547	289.775
2	0	101,325	1.2250	288.150
3	250	98357.6	1.1959	286.525
4	500	95461.2	1.1673	284.900
5	750	92634.6	1.1392	283.276
6	1000	89876.2	1.1117	281.651
7	1500	84559.6	1.0581	278.402
8	2000	79501.4	1.0066	275.154
9	2500	74691.7	0.95695	271.906
10	3000	70121.1	0.90925	268.659
11	3500	65780.3	0.86340	265.413
12	4000	61660.4	0.81935	262.166
13	5000	54048.2	0.73643	255.676
14	6000	47217.6	0.66011	249.187
15	7000	41105.2	0.59002	242.700
16	8000	35651.6	0.52579	236.215
17	9000	30800.7	0.46706	229.733
18	10,000	26499.9	0.41351	223.252

Source Atmosphere [15]

Migration Within the Boundary Layer

A layer close to the ground at which air-speed increases above the wind-speed is known as ***Boundary Layer***. This varies from insect to insect due to their independent airspeeds. An insect can orient and progress to any particular direction within the boundary layer and at high altitudes it will prefer downwind [16].

A butterfly species (*Asciamonuste*) flies at low altitudes of only 1–4 m above the ground levels and is capable of flying against the wind speeds of around 10 km/h. Generally the direction of its migration will be from north or south. The trend of migration in such insect flight is fixed, and they follow landmarks like roads, coastlines etc. Such migration has been reported in queen wasps and bumblebees (*Bombus*) during spring season.

Beetle *Melolontha* also migrates within the boundary layer, and its initial orientation is visual and gets supplemented by orientation of sun or pattern of polarized light from sky [17].

Daytime Migration Outside the Boundary Layer

Thermals arising from the ground due to heat during daytime and the air will be turbulent. Fu et al. [18] confirmed long distance insect migration in airflow due to increase in ground temperatures. Many smaller insects are carried by these thermals above their boundary layers followed by the transportation due to winds. In this method an insect can be lifted to a height of above 3000 m from the ground levels.

However, the migration of insects under very low illumination levels remains to be explained [4]. Chapman et al. [19] also summarized that the insect migration above 12 m remains to be elucidated fully. But during 1947–1948 some radar engineers reported the recorded echoes, suspected to be produced by insects from lower atmosphere.

Crawford observed two wavelengths (3.2 and 1.25 cm) at lower atmosphere and attributed them to be due to insects and birds [20].

Migration at Night

Insect migration during night was observed by using radars as in the case of grasshoppers, locusts and moths. These migratory insects takeoff in larger groups after sunset and otherwise they climb up to a distance of 1000 m. This height varies with species to species. By flying so high these insects are allowing themselves to get out of boundary layer and migrate with downwind. During downwind some insects will have common orientation and it results to a faster displacement with wind speed allowing the insect to travel even 100 km or more (viz. leafhoppers, moths) [5, 21].

Due to the difficulty of visual information at night, these migrating insects exhibit random patterns of flight headings to follow the downwind [4, 5].

Navigation—A General Overview

A sense of navigation and orientation is needed for the migratory insects to identify the wind-speeds and directions so as to make a suitable correction in their flight schedules. They use sun for orientation during daytime based on the movement of sun. Some of the butterfly takes demonstrated endogenous time compensation mechanisms when they were kept in darkness.

The insects are capable of sensing polarized light in cloudy sky as in birds. Some researchers also reported that the migratory butterflies also use earth's magnetic fields by sensing the magnetic particles [22].

The wind-speed and its direction also influence the migration. Some of the insects make use of the wind-speed for their migration by flying to high altitudes. They reach to certain levels of heights and flow with the help of prevailing winds.

It has been reported that birds use the visual land marks, star patterns, sun as a compass, moon orientation, meteorological conditions, geomagnetic fields, polarized light, infrared, olfactory sense, mental maps, visual and sound vibrations and gravity. The integration of all these features during migration in insects remain to be elucidated fully [23] (Table 10.2).

Summary

The study of insect migration helps us to understand different scenarios and mechanisms involved with low body mass, low Re and fliers travelling with low velocity. The physics involved with low Re and low velocity is still to be explained. The role of insect antennae and sensory hairs (*Tricobothria*) for pressure detection and feedback system remain to be elucidated fully. The aerosol problem and wind gusts may interfere with small biological fliers. These ideas are to be considered carefully while designing low speed man made fliers like MAVs. Long distance migrating insect body and derived flight parameters may form the basis for MAV body and wing design. In the MAV design it is possible to make use of bio-mimicking principles from small biological fliers. Any bio-mimicry at the level of flying organism, or wings, or physiological principles or at the molecular level contributes to bio-mimicking. In the present state of knowledge it is not possible to use and incorporate the body and flight parameters directly since it involves a careful scaling and design of nano-aerial vehicles, which are primitive as for experimental designs are concerned.

The interrelationships of various types of migrations including diapauses and environmental conditions are beyond the scope of present article.

Examples of some migratory insects [7, 24].

Table 10.2 Migration

Piloting by
1. **Visual Landmarks**: Mountains, Forest, deserts, Sea and Sea coast, Rivers, Large lakes, High ways. Diurnal fliers make use of mountain ranges, long rivers and high ways for prolonged long distance flight
2.**Celestial and astronomical bodies**:
a. Sun and sunlight (VIBGYOR-visible spectrum)—Sun as a compass
b. Bright star pattern and planetarium Experiments
c. Moon orientation- In Arctic region sunlight is continuous and magnetic directions are not clear
d. Rotation of polarised light along with the sun reveals North direction on a partially cloudy day
3. **Geomagnetism**: Cellular Fe_3O_4 particles respond as Magnetic Radical pair-reaction mechanism for Magneto-reception (RPRM) has been discussed in last chapter
4. **Meteorological and Geophysical conditions:** Atmosphere and weather features
5. **Sense Organs**: Eye, Ear (Ultra sound in Bats), Nose, Sensory hair. Light consists of Infra and Electro Magnetic Vibrations (EMV), VIBGYOR, UV and IR. Visible spectrum λ and ν_h
6. **Optical flow**: Horizon, height and velocity
7. **Circadian rhythms**: Hormonal (Physiological)
8. **Wind speed and its direction**
9. **Memory and Brain**
10. **Genetic Programming (Inherited Navigation Capacity)**
11. **Aerodynamic Formations**
12. **Endurance during Migration flight: (L/*D*** ratio is usually high)
Long distance migration is found in some Insects, Aquatic animals, birds and mammals

* Information from varied sources is compiled

1. ***Schistocerca gregaria***—"migratory locusts" long distance (4500 km) flier.
2. Monarch Butterfly—long distance flyer from Canada to Mexico (3500 kms).
3. Lady bird beetles—the predators of aphids—carried by updrafts-odour helps in migration.
4. Aphids—carried by wind and (attracted by light) some are sedentary.
5. Honeybees and Ants are known for homing instinct, communication and navigation. Honeybees recognize and use landmarks for flight.
6. Ants are known for their homing ability. Ants use the Sun as a compass. Ants and bees have a "Map sense". Desert ants are known for path integration.
7. Owlet moth (Noctuid)—Migrates from Europe to Mediterranean and breeds along the migratory route. They also make use of earth's magnetic field.
8. Dragon fly migrate 100–1000 kms. Returning dragonflies come from different generations.
9. Many species of butterflies in Southern India migrate before monsoon.

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Chapter 11
MAV Design Aspects Using MEMS

Suryanarayana Palleboina and Kamalakar Pallela

Abstract Use of MEMS (Micro-Electro-Mechanical Systems) for biomimicking aerial vehicles (MAV's) is an opportunity and also a new challenge for semiconductor technology. The capabilities and limitations of MEMS are important to consider them for design of biomimicking MAVs. A systematic approach is necessary to identify various components such as mechanical parts of body, wings, sensors, communication system and compatible electronic components. The unit process has to be optimized for mechanical parts by designing a PEV (Process Evaluation Vehicle). Testing the specifications of the components is a must. Hybrid material can be used for biomimicking wings.

Keywords MEMS · Integrated circuit (IC) · Mechanical gear system · Actuators · PEV

Introduction to MEMS

Micro-Electro-Mechanical Systems, or MEMS, are a technology that in its general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro-fabrication. The critical physical dimensions of MEMS devices can vary from one micron at the lower end to several millimetres. Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality.

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This technology was evolved from Micro-electronics revolution and extensively used in manufacturing various devices, such as pressure sensors, accelerometers, flow sensors, inkjet printers, deformable mirror devices, gas sensors, micro-motors, and micro-gears. In recent times the market growth and demand for MEMS is increasing at a rapid rate due to wide range of applications in designing various military, civil and bio-applications. They are critically used in Integrated Circuit (IC) technology, mechanical, chemical and electrical engineering, material science and fabrication technology [1].

MEMS technology is having its impact on Microwave Communication Systems, Phased Array Beam former, EW Transmitters and Space based Radar Systems. All the above systems use switches, which are limited by insertion losses. At present most commonly used switch devices are PIN diodes, GaAs FETs and Conventional mechanical Switches.

MEMS are preferred as they can realize similar to Very Large Scale Integration (VLSI) process technology, which is well established. The fabricated structures can be integrated with MMICs (Monolithic Microwave Integrated Circuit) as well as VLSI circuits. The fabricated structures have good mechanical properties as well as good electrical performance like:

- Very good isolation and low insertion losses.
- Low circuit power consumption in either ON or OFF state.
- Switching speed is sufficient for control; and
- Reliable Systems.

Background of MEMS

The studies on MEMS are being carried out since 1960s and first device appeared in 1970s. However, a boost from public interest allowed this technology get funding from various government agencies [2]. In 21st Century, MEMS are considered to be the most promising technologies to revolutionize industrial and consumer products by using Si based microelectronics and machining technologies. They consist of mechanical micro-structures, micro-sensors, micro-actuators and micro-electronics integrated on a Silicon chip. The devices designed using MEMS are very small and components are microscopic. However, many components like levers, gears, pistons, small motors and even steam engines are fabricated using MEMS.

In general, the term MEMS is also referred to be Micro System Technology (MST), but sometimes it is also considered to be a subset of MST as it deals with the creation of tiny mechanical devices or systems. Apart from this MOEMS (Micro-opto-electro-mechanical Systems) are also considered to be the subset of MST (Fig. 11.1).

The terms transducer, sensor and actuator are mostly used terms in MEMS technology and they are defined as follows:

Transducer: It is a device that transforms one form of signal or energy to other form. It is generally used with both sensors and actuators.

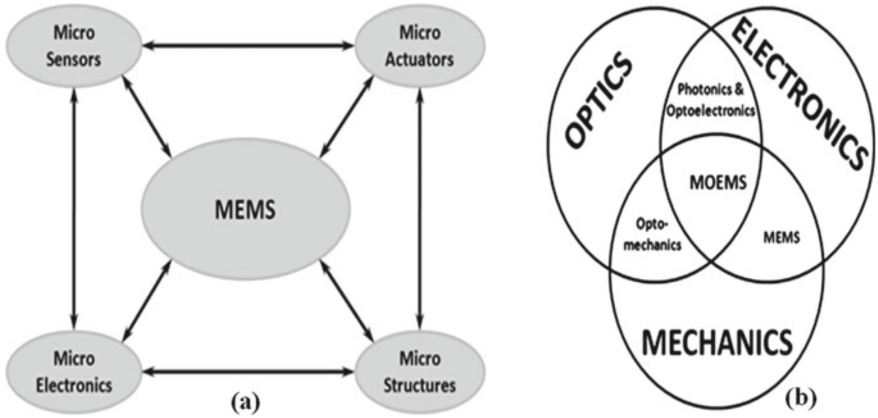


Fig. 11.1 **a** MEMS components and **b** MST and its classification

Table 11.1 Applications of MEMS based on energy domains

Mechanical	Force, pressure, velocity, acceleration, position
Thermal	Temperature, entropy, heat, heat flow
Chemical	Concentration, composition, reaction rate
Radient	Electromagnetic wave intensity, phase, wavelength, polarization reflectance, refractive index
Magnetic	Field intensity, flux density, magnetic moment, permeability
Electrical	Voltage, current, charge, resistance, capacitance, polarization

Source Extracted from Prime Faraday Technology Watch [1]

Sensor: It is a measuring device, collects the information from surroundings and provides an electrical output signal with respect to the measured parameter. Based on the type of energy domain the MEMS applications are categorized.

Actuator: It is a converting device and converts electrical signal into an action. It creates forces to manipulate itself or other mechanical devices or surrounding environments to do some useful function (Table 11.1).

Role of MEMS in Various Applications

The wide ranges of MEMS found in different applications in multiple markets are listed below (Table 11.2).

Table 11.2 Applications of MEMS based on industrial application

Automotive sensors	Internal navigation	Air conditioning compressors	Brake force and suspension control accelerometers	Fuel level and vapour pressure	Airbag	Intelligent tyres
Electronics	Disk drive heads	Printer heads of inkjet type	Televisions with projection screens	Earthquake sensors	Avionics pressure sensors	Mass data storage systems
Medical	Blood pressure sensors	Muscle stimulators and drug delivery systems	Implanted pressure sensors	Prosthetics	Miniature analytical instruments	Pacemakers in cardiology
Communications	Fibre-optic network components	RF relays, switches and filters	Projection displays in portable communication devices and instrumentation	Voltage controlled oscilloscopes (VCOs)	Splitters and couplers	Tuneable lasers
Defence	Munitions guidance	Surveillance	Arming systems	Embedded systems	Data storage	Aircraft control/navigation

Source Extracted from Prime Faraday Technology Watch [1]

Advantages of Using MEMS in Various Applications

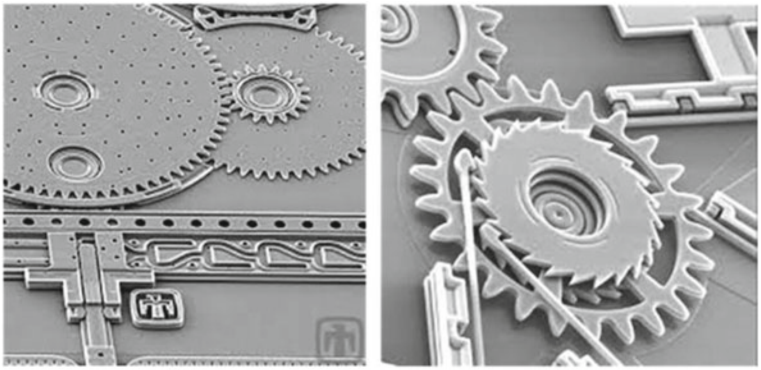
Several advantages of MEMS as a manufacturing technology include various aspects. The interdisciplinary nature of MEMS technology and micro level machining techniques allowed it to diversify its applications, which resulted in wide range of unprecedented devices and synergies across various unrelated fields such as in biology and electronics. Usage of batch fabrication techniques in designing MEMS allows enabling components and devices to be developed and manufactured with high reliability and improved performance. Apart from these, this technology also allows to reduce the size, volume, weight and cost. This technology also provides a basis for manufacturing the products beyond the imagination of any one by using its specialized techniques compared to other existing techniques. However, many challenges and complex technological obstacles related with miniaturization needs further study at micro level in multidisciplinary subjects [1].

Role of MEMS in Designing Bio-mimicking MAVs

Sensory devices: Wide range of sensory devices is designed and fabricated using MEMS technology for their adaptation towards miniaturization of electronic and mechanical equipment's in the market. The sensors like automotive airbag sensors and medical pressure sensors can be included in MAV design. Airbag sensors are now-a-days used to detect the deceleration of vehicles by measuring the changes in voltage. Additionally if we used electronic controls on these sensors, the same can be designed or for the applications of guided MAVs.

For an example, the vehicles designed by BMW, 740i vehicle used more than 70 MEMS working more effectively. Various functionalities of MEMS applications include anti-lock braking system, active suspension, navigation control systems, monitoring vibrations, fuel sensors, noise reduction, rollover detection, seat belt restraint and tensioning. Similar characteristics may be needed for designing a bio-mimicking MAV as all these properties can be implemented with reduced size. In the market, airbag accelerometers are even available for detecting earthquakes, video games, weapons and high performance disc drives. On the other hand, sensors designed by using MEMS are used to measure and monitor blood pressures [1].

Mechanical Gears and Components: The flight of a natural flier involves various aerodynamic aspects like generating lift, thrust, twists and various rotational movements. To implement such a model of complex actions using general mechanical components will be a tough task due to limitations or restrictions on weight and size of an MAV design for the flight. Using MEMS various components with the ability of performing complex actions including controlled gears can be designed for low dimensions. Some of the motor gears and gear systems developed by the authors have been shown in figure which are used for space and satellite communication applications at micro level (Fig. 11.2).



(a) (b)

Fig. 11.2 **a** Motor gear fabrication. **b** Mechanical gear system

For Aerodynamic Controls: There are many MEMS fluidic sensors in the market included with piezo-resistive pressure sensors, micro machined hot wires and shear stress sensors allowed them to use for flexible bubble actuators, which affects rolling movements of the wing. Apart from the above advantages, the actuators designed using MEMS are power thrifty and hence they are efficiently used in wide range of applications for the improvement of large aerodynamic performances [3].

Micromachining Process

Designing of MEMS involve various processing steps and a broad classification of these steps are given below.

1. Standard Integrated Circuit (IC) Process
   - This method will be similar to that of IC fabrication
2. Surface Micromachining
   - This is an additive process
3. Bulk Micromachining
   - It is considered to be subtractive process
4. Providing a dividing line and it can be blurred at times.

IC Process

The processing of an IC consists with the following steps:

1. **Lithography**: It is a process of defining pattern by applying a thin uniform layer containing viscous liquid (in general, it is termed as photo-resist, PR) on a water surface. PR is hardened by baking and is removed at selective sections by projecting it to the light with a reticule consisting of mask information.
2. **Etching**: It is a process of removing unwanted materials from the wafer surface in a selective manner. Then this pattern of PR is transferred to the wafer by using etching agents.
3. **Deposition**: Films of different materials in desired forms are applied on wafers. Two methods generally used for this purpose are physical vapour deposition (PVD) and chemical vapour deposition (CVD).
4. **Chemical Mechanical Polishing**: It is a Planarization technique, which uses chemical slurry with etchant agents on the wafer surface.
5. **Oxidation**: Two types of oxidation methods are used, and they are (1) Dry Oxidation (only oxygen is used) and (2) Wet Oxidation (H_2O is used). In this process oxygen or H_2O molecules will convert Si layers on top of wafers to Silicon dioxide.
6. **Ion Implantation**: This method is popularly used to introduce the dopant impurities in a semiconductor. Ionized particles will be accelerated in an electric field and will target the semiconductor wafer.
7. **Diffusion**: This is used to anneal bombardment-induced lattice defects.

Surface Micromachining (SMM) Process

It is a well known core technological process for underlying MEMS from deposited thin films [4]. There are four steps in surface micromachining as shown in Fig. 11.3. An isolation layer is coated to the substrate in Fig. 11.3a to protect it during etching steps. An opening of sacrificial layer is terminated on isolation layer as shown in Fig. 11.3b. A mictrostructural thin layer will be deposited and etched as shown in Fig. 11.3c.

In the final stage only selective etching of sacrifical layers will create a free-standing micromechanical structure like a cantilever beam as shown in Fig. 11.3d. The above steps are extendable for preparing multi layered micro-structures. This

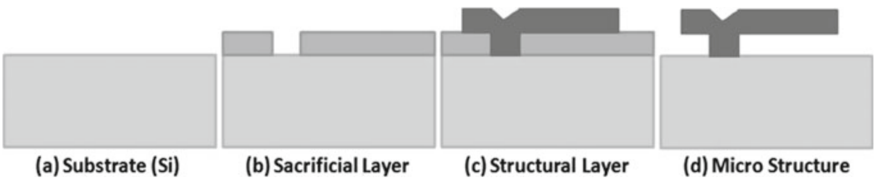


Fig. 11.3 Steps of surface micromachining process

process is more suitable to design the wings of MAV structures in different dimensions based on the material proposed as MEMS technology also supports the biological implantations.

Bulk Micromachining (BMM) Process

This method allows the substrate to be used in three sides of its dimensions. Single Crystalline Silicon is used due to its electrical and mechanical properties. Generally wet etching and dry etching methods are used to design MEMS. Anisotropic etchants such as KOH and TMAH are used for performing the web etching. However, TMAH etchants are highly compatible with CMOS process as these etchants are alkaline ion free.

Practical Considerations of Designing MAVs Using MEMS

Design of an MAV demands various aerodynamic considerations along with its body parts and power sources connected to it at various sections. Silicon is the dominant material used in MEMS for most of the device fabrications and recently soft material like polymers are designed using natural materials. These hybrid systems are biocompatible and for example, parylene is used to fabricate variety of valves and pumps for fluidic applications at micro levels. Ho et al. [3] suggested parylene based MAV wing membrane with a typical thickness. The same material can also be used for electrostatically activated check-valves. Considering the above two reasons MEMS devices can be integrated on the wing, which forms a complete unit.

Ho et al. [3] reported a successful operation of independent actuators at a voltage of 50 V. Fully integrated actuators on these wings are even working up to a voltage of 300 V due to the increase in the gap (d) between electrodes at the time of integration. The general equation for electrostatic force (F_e) is given by

$$F_e = \frac{\varepsilon_o A V^2}{2d} \tag{11.1}$$

where A is the area of two conductive plates.
d is the gap between plates.
V is the applied voltage.
ε_o is the permittivity of free space.

A careful note must be considered at low voltages that the fabrication needs to be done carefully to reduce the electrode gap at the time of integration. Otherwise, the electrostatic forces proportional to demand a voltage rise by its square for maintaining same force when the gap size is increasing.

The role of these actuators can be considered as key area of discussion as they will be playing a vital role in generating the aerodynamic effects if placed at leading edge. On the other hand, check-valve actuators are mounted in the wings in such a way that during downstroke they are closed and are open during upstrokes. The power is spent during downstroke and saved during upstroke [3] which is more or less a recovery stroke.

A strong feedback controlling system can be adopted, and it will be very interesting to maintain desired aerodynamic forces and even to improve the flight performance of the MAV in different conditions. The mechanical wings in an MAV cannot move their wings like biological flapping flexible wings due to lack of muscles, feathers and wing structures. Hence the role of active flow controls and their design will be a key area to focus while designing a bio-mimicking MAV. The biggest challenge in Active Flow Control is to develop a control system to handle the complex problems of aeroelasticity due to structural deformation. This problem in a bio-mimicked MAV will be more complicated if the designed wing structure is containing more number of actuators and sensors. Apart from aeroelasticity, there are other practical challenges for MAV in real time due to wind gust, low weight, aerosols, mist, landing and takeoff.

Another important consideration of MAV flight is related with its wing kinematic motion and its flight mode control during transition periods. A good MAV model needs to take care of rotation of the wing over the longitudinal axis of the body during upstroke and downstroke [5]. These problems can be solved by using a controlled DC motor connected with wings along with a controlled gearing system. By varying the DC voltages the angular speed and wing movement can be controlled according to the desired levels of aerodynamic wing movements.

Process Development of Micromachining

Designing of MEMS involve various processing steps and a broad classification of these steps are given below.

1. Define various set of mechanical structures which are useful in MEMS in Process Evaluation Vehicle (PEV).
2. Write down the Process flow chart to realise the structures.
3. Optimise the Unit Processes independently according to their Fab capabilities.
4. Define Process Control Monitoring (PCM) Limits.
5. Design a set of Masks of each MEMS structure according to unit processes. Depend on process flow, the number of Masks varies up to 10 levels.
6. Realise the PEV and evaluate the performance of the structures and devices.
7. Evaluate which MEMS structures have good performance and good yield.
8. Second Iteration of PEV as mentioned in step 1 and repeat the whole cycle up to step 7.

The process has to continue until good working MEMS based MAV is realized.

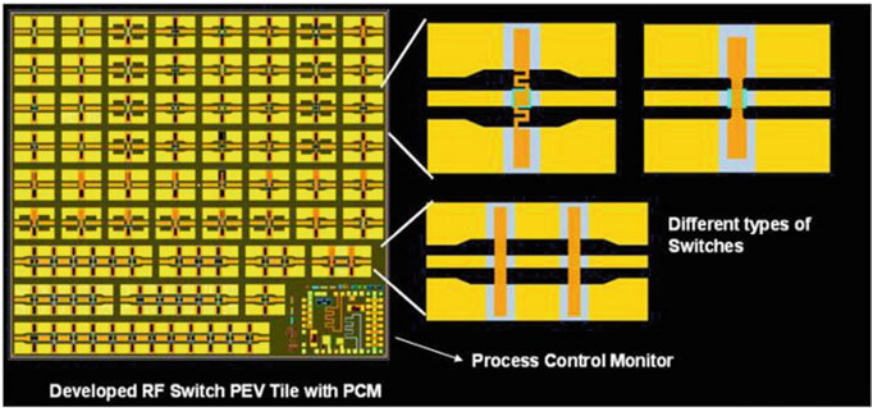


Fig. 11.4 Processing steps to design a bio-mimicking insect (dimensions are not quoted for various reasons)

The author has developed a MEMS process for RF Switch using about 200 structures having various dimensions between 10 and 1000 microns length, 10–400 microns width and with a thickness of up to 3 microns.

Various types of electronic materials such as semiconductors, metals and polymers have been used to optimize the process (Fig. 11.4).

The insect mimicked MAVs mostly need to consider the size and weight as a very important focusing area. Designing a bird mimicking MAVs have the flexibility of selecting range of dimensions in terms of size (2 cm to 4 m) and weight (5 g to 20 kg) [6] (Fig. 11.5).

On the basis of previous knowledge on VLSI technology, MMIC technology and RF MEMS technology over 3–4 decades, the new MEMS based MAV realization technology and methodology is proposed which is promising for future applications. The MAV realization consists of hybrid technology of Semiconductor VLSI, MMIC and MEMS processes.

An insect mimicking MAV with a wingbeat frequency less than 50 cps as estimated for soapnut bug (***T.j***) by using wingloading techniques (N. Chari, personal Communication) can be proposed. The insertion of various control and sensory systems are possible using MEMS technology and will be included at the final stage after forming the wings. The power consumption for such MAVs will be in the range of 1–5 V. However, for a controlled bio-mimicking MAV the power consumption may increase to a range of approximately 10 V.

However, there are some of the open challenges identified in this technology at various levels as given below:

- This technology is new to test the structures for On Line Process Control (OLPC) to improve the MEMS process reliability
- The new electronic material or circuits must improve the mechanical properties
- Process optimization or realizing sticking micro mechanical structures

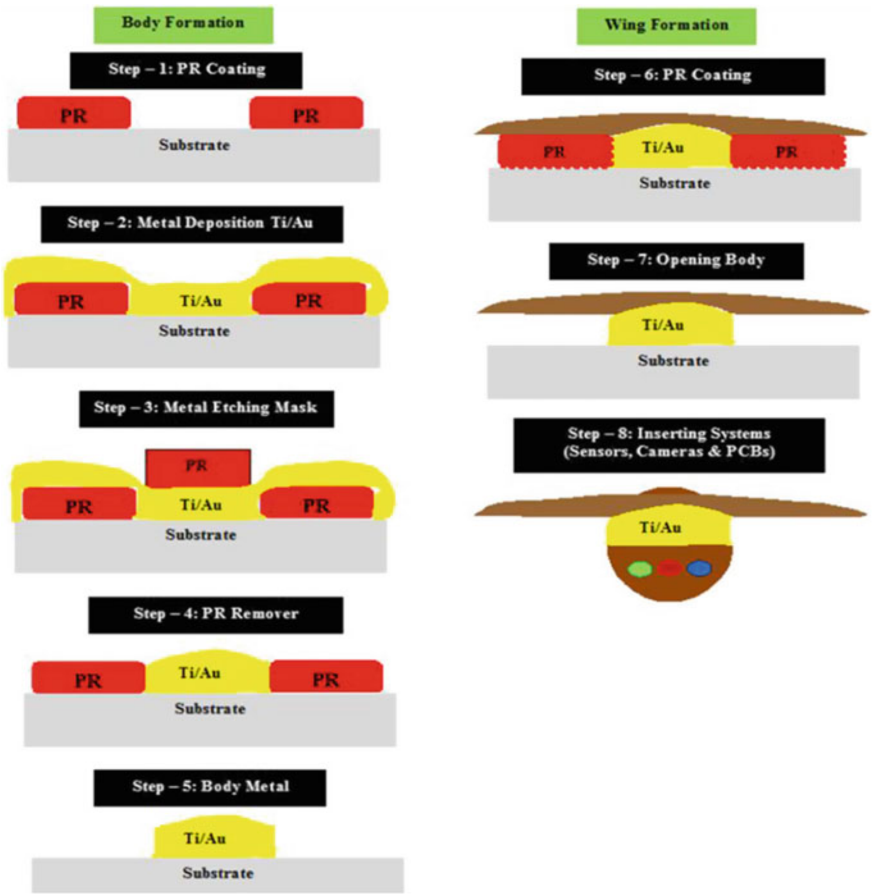


Fig. 11.5 Processing steps to design bio-mimicking insects (Dimensions are not quoted for various reasons)

- Dry processing of MEMS needs to improve yield of MEMS production; and
- A detailed addressing of packaging problems of MEMS needs to be incorporated.

Summary

MEMS for MAV are open challenge for Semiconductors Technology to realize the working MAV. The MAV has to be designed according to MEMS process capabilities. A systematic approach is needed to identify various components such as mechanical parts for flying, sensors, communication systems etc. Process Compatible electronic materials should be identified, and the unit process has to be optimised for mechanical parts by designing a PEV. Similarly the sensor devices and communication

circuits should be designed as per specifications and realize the same. Integrate all the components of MAV and test the performance of the system as per specifications.

Insect wings consist of flexible membranes using chitinous fibrous material and being supported by semielastic veins (see Chap. 4). According to XQ Bao et al. (2011, Micromech Microeng 21, 125050) natural wings can will be mimicked in material conception, weight, venation size, mass distribution and wings rigidity using hybrid material for bio-mimicking MAVs.

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Chapter 12
Bio-mimicking MAVs Based on Insect Flight Studies

N. Chari, Prasad Mukkavilli, and A. G. Sarwade

Abstract A micro Aerial Vehicle (MAV) has characters common with biological fliers within reasonable weight limits. For biomimicking MAVs, weight range, size, aspectratio, wing design, lift to drag (L/D) ratio, speed, wingbeat frequency, landing and takeoff, low *Re* and autopilot systems have to be selected carefully. The insect geometry can be scaled up to 2 or 3 times for an MAV. Insects use different methods of navigation. A simple autopilot with an OBC is a must to measure pitch, yaw and related parameters. Based on the available flight data, the design of experimental biomimicking MAV is discussed. The important components considered for design are; the shape of the MAV, Antennas for transmission and receiving the signals, cameras, gyros, accelerometers (x, y, z) and GPS receivers for navigation, flapping flexible wings with low frequency, Mass (low), wing span loading, and Resilin like elastomers at the wing joint to thorax.

Keywords Low mass · Ar · L/D ratio · Acceterometers · Autopilot

Overview

A Micro Aerial Vehicle (MAV) has many common characters with biological fliers such as insects, birds and bats within a reasonable weight limits. We have insects where weight ranges from 10 μg to about 60 gm and the birds weighing from 2 gm to 20 kg. Being nocturnal fliers having complex navigation bats are not considered for MAV design. Some of the common bioaerodynamic features of biological fliers, which could help us in understanding the design of MAVs are considered in the following sections.

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Discussions on bio-mimicking MAVs intend to have a streamlined body for reducing the drag and increasing the associated aerodynamic forces. However, the power source is the battery and not the biological contractile oxidative muscles. It is not possible to use flight muscles for the production of power as in real insects. The flight muscles of insects, birds and bats are more sophisticated and more complicated in their cellular structure, attachments and the functions. Although a number of experiments have been carried out for the synthesis of artificial muscles, it has not been possible to achieve control on their contraction and relaxation as it happens in biological systems. There is a superior feedback control systems acting in milli-seconds, regulated by neuronal mechanisms and structural characteristics.

Following are some of the specific and necessary aspects for different MAVs, which share common characters between them:

1. **Weight Range**—20 to 250 gm for the Bird-mimicking MAVs and 100 mg to 60 gm for Insect Mimicking MAVs.
2. **Size**—The maximum size can be about 40 cm (400 mm)—that would represent the wing span for bird model MAVs and 5–6 cm (50–60 mm) for insect model MAVs.
3. **Aspect Ratio**—Range 2–3.
4. **Wing design**—Copying the membranous wing of insects is easier than to copy the wings of birds and bats, which are highly complex in their structure. Insect wings are made up of *chitin*, a polysaccharide amine thin membrane. These wings can develop differential aerodynamic forces during up and down stroke movements. The flapping of wings in biological insects and birds is possible due to aeroelastic properties of different components of the flexible wings and wing joints.
5. **Lift to Drag (L/D) Ratio**—This is relatively low for such models.
6. The **maximum speed** attained by these fliers has to be restricted to 30–40 km/hr (approximately 8–10 m/s). There is quite a possibility that these light MAVs might be carried away backward and lose their way if there is a gust wind, flowing in the opposite direction.
7. The suggested **wingbeat frequency** can be restricted to be in the range of 10–20 cps, keeping in view the bio-acoustic sound levels, which are significant in bio-mimicking designs.
8. In an insect flier the proximal area of the wing, which is attached to the thorax by an elastic hinge is broader and thicker leading to a distal membranous area. The proximal area develops required lift; the distal area helps in the contribution of thrust and the wing tip in the development of induced drag due to vortices. The shape of the wing may be chosen to be roughly rectangular or elliptical. These aspects in general require careful study while selecting the wing shape and structure for bio-mimicking MAVs.
9. MAVs have a serious problem of landing and takeoff as compared to the natural fliers. It may be possible to adopt the landing and takeoff system similar to the Perching Mechanisms of natural fliers. This perching action is being practiced

and perfected by all natural fliers. It was even present in certain feathered Dinosaurs.

10. The autopilot system, which would be incorporated in the MAV, should take care of aerial manoeuvres and possible aerobatics including complex landing and takeoff manoeuvres.
11. These MAVs may have to play a crucial role in the survey of nearby enemy targets and also might help in recording sound and capture videos or pictures. The MAVs can also be used for paramilitary and civilian activities.

The MAV flight becomes more complex in different terrains and environments including the design of MAVs for night flight operations. MAV research projects need a very close inter-disciplinary collaboration between Biologists, Ornithologists, Physicists, Mechanical Engineers, Aeronautical Engineers, Aeronautic Designers and Navigation experts. Recent developments in nanotechnology and material science would help in arriving at suitable materials for the body, wings, wing fixed joints and perching mechanism. However, the aeroelastic aspects of the structural properties would remain an open challenge for these fliers because one has to carefully study basic properties including axial stretching, buckling and damped vibration characteristics of these materials. Our present knowledge of aeroelasticity of aeroplanes can hardly be applied to MAVs as these fliers are small, delicate and cover low speed having low Re flights. Resilin like protein elastomere has to be attached at the wing base joint to contribute for high frequency flapping flexible wings. The wing design also will considerably differ from that of conventional aircraft wing and other homoeotherm fliers.

Adaptability of Different Wing Configurations for MAVs

There are three basic types of wings those could possibly be adapted for different types of MAV models. The table as suggested by Chari [1] has been completely revised in Table 12.1.

Relevance of Insect Flight to MAV Applications

It has to be mentioned that historically the natural fliers consisting of insects, birds and bats have been flying in nature since 300, 250 and 60 millions of years respectively. It is through a long process of evolution controlled by genetic and environmental constraints. This flight study is important in view of the fact that there are many features common to both insects and Insect Mimicking MAVs. Some of the important features common to the two categories are low mass, low size, low Reynolds number, low aspect ratio, low L/D ratio and low velocity. Both insects and Insect Mimicking MAVs are susceptible to wind gusts. Insects are natural fliers and provide

Table 12.1 Comparison of fixed, rotary and flapping wings

Parameters	Fixed wings	Rotary wings	Flapping wings
Aerodynamic forces developed	Vertical lift opposing drag and no thrust	Lift, drag and thrust	Lift, drag and thrust
Fulcrum at the wing base	Wing rigidly fixed at the base	Hinged to central rotor hub; free to tilt up and down and turn about the longitudinal span wise axis	Elastic hinge and movable; possibly in X, Y, and Z directions
Propeller or jet (optional)	Usually separate propellers are present	No separate propellers	No separate propellers
Acoustic level	Relatively high	Very high as in helicopters	Variable; depends on wingbeat frequency
Wing tip velocity	Constant	Constant	Variable, linear and rotating
Aeroelastic effects	Present	Present and more critical	Present and more critical
Wing motion	Wing rigidly attached, moves along with the body	Circular (rotary) and with up and down oscillations	Oscillating and twisting type of motion
Wingtip traces	Practically straight line	Circular superimposed with up and down oscillatory motion	Elliptical or figure of '8' depending on frequency
Stalling angle (onset)	15 to 20°	15 to 20°	Up to 70° or more
Landing/Take off	Long run way is required	VTOL (Vertical Takeoff and Landing); no runway required	Need some runway (STOL or V/STOL) for MAVs
Rotary tail fan	Absent	Required to counter rotor torque	Absent
Manoeuvrability	Limited	Torque of the moving rotor is relatively high. Hence limited	Relatively high
Translatory motion	Forward, long and small distance flight	Forward and backward, VTOL	Forward and occasionally backward

Source Adopted and modified from Chari [1]

inspiration and provide many useful clues in the design of small man-made aerial vehicles by incorporating flapping and flexible wings. The microaerial vehicles and unmanned aerial vehicles (MAVs and UAVs) share many common characters with the biological fliers. Presently there is an increased demand for the deployment of MAVs for surveillance applications, paramilitary activities, civilian applications, military and environmental missions for spying and surveillance. This is equally true for both the advanced and developing countries. The design and production of successful MAVs is still in experimental stages. There is also a serious problem of takeoff and landing of MAVs as compared to the biological fliers. Biological fliers could overcome these problems through a continuous process of evolution lasting over millions of years, which involved both genetic and ecological adaptations. Therefore multidisciplinary research and close coordination is absolutely necessary between biologists, physicists and robotic engineers for developing successful models of MAVs based on bio-mimicking principles of flight and landing techniques.

Insect flight is considered as an evolutionary and adaptive model for miniature flight design. Flight of an insect is still a mystery. The forces acting on flapping wings are quasi-steady and unsteady, which may lead to higher lift forces as compared to the conventional lift generating devices. The wingbeat cycle is usually expressed as cycles per second (cps) or Hertz (Hz). However, a single flapping wingbeat cycle consists of a powerful downstroke and a recovery upstroke each lasting only a few milliseconds. The wingbeat basically leads to both translatory and rotational movements. These strokes are usually described in terms of three basic angles viz., sweep angle, roll angle and angle of attack. In a flapping cycle, there are two rotational stages: one is supination and the other one is pronation. During supination, the wing begins to flap from behind the body. During pronation the wing rotates at the fulcrum and also changes its direction where the leading edge is ahead as explained by Wilkins and Knowles [2].

Reynolds Number and MAVs

Reynolds number (Re) is defined as a ratio of inertial forces to viscous forces, usually in terms of fluid flow and geometrical parameters of the flier. It can be expressed as follows:

$$\mathrm{Re} = \frac{(inertial\ forces)}{(viscous\ forces)} = \frac{(total\ momemtum\ transfer)}{(molecular\ momemtum\ transfer)}$$

In biological flight viscous forces are more predominant as compared to inertial forces and the Reynolds numbers are relatively low. It may be noted that Re is a non-dimensional parameter. Acknowledgement of Re is important in bio-aerodynamic studies because the lift and drag development depend on Re value. At low Reynolds number, it is difficult to keep boundary layer attached to the surface of the flier. It has to be noted that Reynolds number values for insects vary from 10^2 to 10^4 while for homoeotherm fliers it is in the range of 10^4–10^6. However, for an aircraft it is usually above 10^7. For small insects like thrips, Re is very low and viscous forces are dominant. Re also helps in understanding the flows such as laminar, transitional and turbulent. Re values are substantially low for sperms, algae, protozoa and fungi (see Fig. 12.1). As flyers size reduces Re also becomes lower.

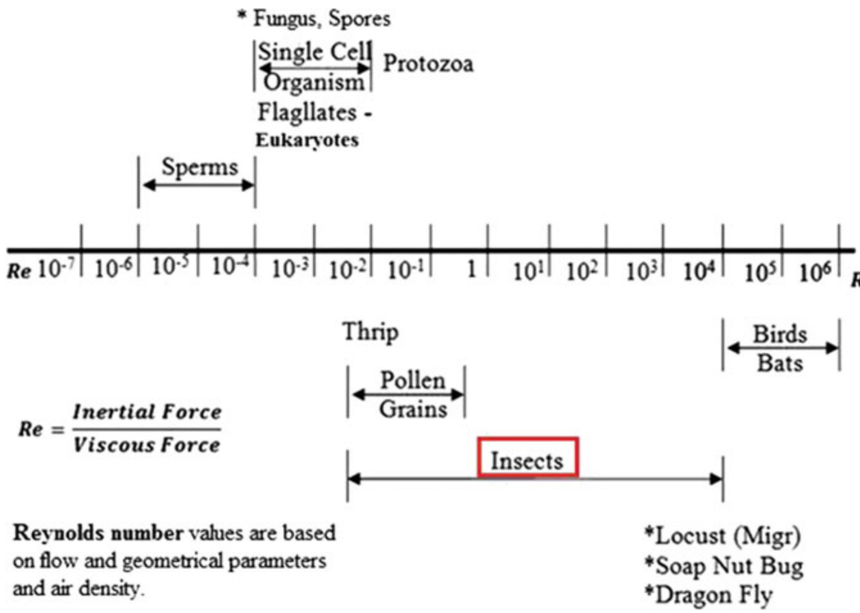


Fig. 12.1 Variation of Reynolds number in biological fliers [3]

Additional Aspects to Be Considered for MAV Design

The following are some of the additional factors which need careful attention in the Insect Mimicking MAV Design and Development.

(a) Data bank of flight of larger flying insects suitable for MAVs
(b) MI studies on insect wings and MAVs
(c) Non-dimensional numbers and their significance in MAV studies
(d) Additional lift enhancing devices such as those in present insects.

Bio-mimicking MAVs Design Based on Insect Flight

MAVs can be used for observation or surveillance of remote areas and offer many applications in civilian and military sectors. The flapping wings are aerodynamically more efficient than fixed wings; hence, it is advantageous to use them for MAV design. Bio-mimicking of the insect flight may be easier as compared to the bird flight because the insect wings are chitinous membranes, as opposed to the complex feathery wings of birds. The bird wings on the other hand also have a complex network of nerves and muscles for flight control, which is difficult to replicate in MAV design. Hence it is relatively easier to develop insect mimicking MAVs as compared to Bird-Mimicking MAVs. The challenge, however, lies in the miniaturization of different constituent components due to the very small masses of insects and their flight components to be replicated.

Choice of an Insect for Bio-mimicking

About seventy five thousand insects exist in nature. Considerable work has been done on the Soap nut bug (*T.javanica*) in India by Chari [1] and his associates. The geometry of *T.j* is useful and adaptable for designing a bio-mimicking MAV. Some of the reasons to select *T.j* are listed below:

(a) The body structure of *T.j* is more suitable for accommodating various internal components to design MAVs.
(b) Structurally its body is more rigid. The body contains only two parts i.e., an upper spherical disc and a lower elongated disc. The lower disc can support the internal components and the upper disc is just a cover, fitting over the lower disc by a simple tongue and groove joint. Such discs for MAVs can be easily manufactured by moulding the two parts using Fibre Reinforced Material Plastic (FRP) which can offer high structural rigidity.
(c) Its body as viewed from top is of circular dish in shape (*scutellum*), which offers less drag. The abdomen is more or less a truncated frustum and sternum is one continuous boat like plate.
(d) Complete thorax and part of the upper abdomen is covered by scutellum, which is ideal aerodynamic device for reduced drag and enhanced fast air flow.

Salient Features of the Insect **T.javanica** *and Its Adaptation for MAV*

The following suggestions are favorable for the adaptation of *T.j* model to design an MAV:

- The insect geometry can be scaled up to 2 times for MAV design. The full-scale width of body of the insect is 20 mm. Magnification is needed to a certain extent to accommodate various internal components of MAV. The limitations in the degree of feasible miniaturization of the internal components appear to dictate the magnification factor.
- The diameter is estimated by the size of thorax and limited by the MAV sizes.
- The two pairs of wings of *T.j* on each side can be merged into one pair for the practical MAV, for simplicity. They can have winglets to reduce the induced drag.
- Antennae (one pair) in the front (similar to those in the actual insect) for transmission and reception of radio signals.
- The three pairs of legs of the insect can be replaced by a pair of brackets (one vertical and the other horizontal, on the ground). The bottom bracket can act

as a landing and take-off pad, with shock absorber material like rubber/nitrile rubber/Si material.

Navigation of MAV

Estimating the position, orientation and velocity of a flier is navigation. Navigation is a process of identifying the instantaneous values of the flying object position in terms of co-ordinates (x, y, z). It is measured from a known origin along with the direction and the velocity of flight. In simple, it is to estimate the position, orientation and velocity of a flying object.

Collett and Collett [4] explained the usage of path integration by insects, which requires a way of storing states of accumulator at significant places to recall the goals subsequently and a kind of computing the direction to reach the required goals. Most of the migrating insects use the navigation as a tool, and they use different methods of navigation. For example, honeybee foragers communicate the position of food sources using their waggle dance and by path integration so that the rest of the bees acquire the information. The location of the food is obtained from the dance signals in terms of direction and distance from the hive. Direction is defined in terms of horizontal angle made by feeder, hive and azimuthal position of sun. Similarly, ants are reported to be the insects using path integration successfully to reach their destination. However, desert ants are also found to use vector navigation techniques to reach food sites. A forager to perform path integration needs to monitor changes in position by updating a kind of accumulator.

The ability to navigate needs two additional features: Recording and Comparator. Recording feature explains the recording of the accumulator state of destinations. In comparator feature, it explains each current accumulator state by subtracting from the total recorded states. In simple, vector navigation explains the collection of various processes updating accumulators, recording the state of accumulators and comparing current and recorded states of accumulators to direct the movement to reach the destination.

Considerations for Bio-mimicking MAV Designs

The conceptual trajectory of MAV can be as follows:

a. The trajectory in level flight to reach an area of surveillance must be relatively at a shorter distance with short takeoff
b. Hovering or circling flight is needed at the area of surveillance
c. The MAV needs to return to the launching point (pad) after finishing the surveillance task.

In the above process hovering needs more power than circling or horizontal level flight. The power consumption during hovering is more than 10 times as compared to other modes of flight.

Navigation Equipment for Bio-mimicking MAVs

a. **Artificial Horizon**: It helps to maintain horizontal level flight and during hovering it also helps to measure angle of attack or altitude angle (Fig. 12.2).
b. **Altitude Sensor**: It helps the flying object to fly at a predetermined height '*h*' above the ground level. These sensors play a vital role in avoiding the collision of flight.
c. **Flight Direction Sensor**: These sensors help the MAV to navigate with the help of GPS systems available in the market. The launch point will be considered as origin for the co-ordinate system in MAVs. However, the whole navigation system works only during the availability of power supply. Otherwise MAV will stop functioning and cannot navigate on its own unlike the other natural fliers.
d. **Control Systems**: A relatively simple 'Autopilot' with On-Board-Computer (OBC) to generate and implement control deflections as per the control law (preferably derived from wind tunnel tests) with simplifying assumptions for the lift equation.

For a given speed and altitude the lift equation is given by

$$Lift = K_1 a + K_2 \delta$$

where K_1 and K_2 are constants.
a is the angle of attach (AOA).
δ is the wing tip depletion angle for control.

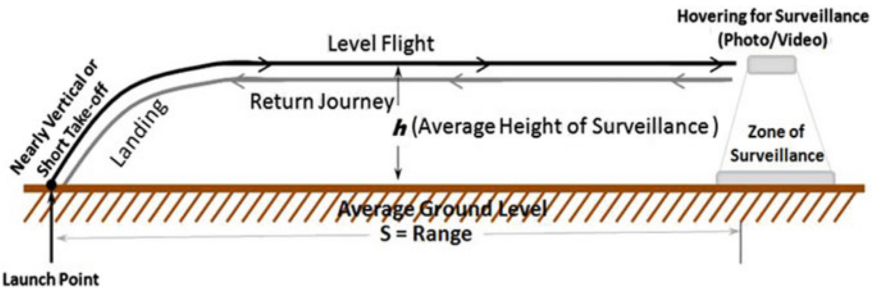


Fig. 12.2 MAV trajectory path during surveillance (conceptual)

Additional Aspects of Surveillance

1. Externally the bio-mimicked MAVs should resemble insects/birds/bats in its appearance.
2. The speed of MAV can be taken as 20–30 kmph (approximately 5.6 to 8.3 m/s).
3. The altitude '*h*' can be fixed with reference to that of the launch point (1 km).
4. During the initial space trials/demonstration of navigation, the range 'S' of MAV can be less (for reducing battery power).
5. The main function of MAVs is to transmit the captured signals (audio/video) from the area of surveillance to the launch point.
6. Special attention is needed while considering the sounds generated by the MAV during flapping so as to keep up with bio-mimicking acoustic levels.

Summary

Salient Features of Insect Flight forming the basis for Bio-Mimicking MAVs may be summarized as follows:

1. Species-specific aerodynamic parameters may help in the better selection of bio-mimicking MAV models.
2. Low mass: 2–10 gm maximum.
3. Moderate wingbeat frequency (10–20 cps) with a higher wing area through suitable scale up (~2:1) to match the requirement of the MAV.
4. Low Re range of operation: 10^2–10^4.
5. Resilin like elastic fulcrum (protein elastomere) at the wing base.
6. Flexible flapping wings with full control over the wing movement to develop lift and thrust. These wings are capable of undergoing elastic structural deformations during flight while withstanding the wind loads.
7. Low Wing Aspect Ratio: Typically 2–3.
8. Low flight velocity: 20–30 km/h (5.7–8 m/s).
9. Flow physics of small insect fliers with low Re is not fully understood hence it needs further detailed study.
10. Enough care has to be taken for incorporating features for takeoff and landing capability. Unfortunately, these aspects are still in primitive experimental stages.
11. Wind tunnel tests and CFD studies are needed to for the successful experimental design.
12. A bio-mimicking MAV should be capable of hovering and circling in addition to horizontal motion.
13. Data bank on insect flight in the selected category (such as migratory fliers) needs to be compiled and analysed for getting realistic results with the MAV design.

14. VTOL/STOL capability for the MAV may be an additional requirement for effective operation.
15. The Mems have been developed for several years for sensors and Mechanical systems.

The wings of the insect with micro level sized are capable of recovering from stall due to existence of prolonged pre-stall zone covering wide range of angle of attacks. This feature in biological fliers is possible by virtue of inherent fast sensory perception and feedback mechanism controlled by brain.

Practical Limitations:

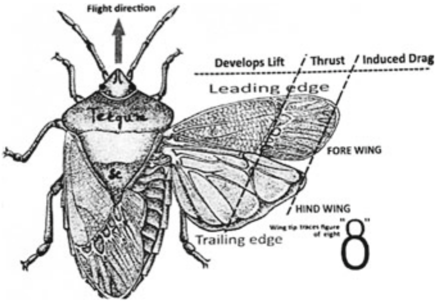
1. Small size of MAV for ground Station Observation beyond 100 m is a real problem.
2. MAVs cannot carry on road transmitters but allows remore observation.
3. An autonomous MAV may be analogous to biologically inspired entomopter.
4. The distance travelled and the time required are too limited for practical use.
5. Landing and take off still remains a problem for such aereal vehicles.
6. DARPA has a programme to develop MAVs similar to entamopters.
7. Winds drifting is a real problem.

Some of these problems have discussed in an International Symposium in Switzerland recently (Table 12.2).

Table 12.2 ***Tessaratoma javanica*** bio-mimmicry model data

S No	Parameter	Units (CGS)	*T.j*	*T.j* model	Ratio
1	Mass (M)	Grams	1	4	4
2	Wing length (l)	Cm	2.2	5	2.27
3	Wing breadth (B_{eff})	Cm	1.13	2.6	2.30
4	Wing area (2A)	Cm	10	25	2.5
5	Wing span (L)	Cm	6	12	2
6	Wing loading (WL)	Gm/cm^2	0.2	0.16	0.8
7	Wing span loading (WSL)	Gm/cm^2	0.02	0.027	1.35
8	Aspect ratio (AR)	–	7.2	5.7	0.79
9	Wing beat frequency (ϑ_h)	Hz	51.2	23.17	0.45
10	Time period (T)	Sec	0.019	0.043	2.26

Note MAV of ***T.javanica*** shall be of hemispherical elongated shape because of the tergum and convexo-concave scutellum to accommodate the delicate internal nano components i.e. Autopilot, feedback control loop, batteries, telemetry (antennas), camera, GPS receivers, pilot static tube and flapping flexible wings with moderate frequency. Antennas are of transmission and receiver type. There will be OBC to measure pitch, yaw and row angle (φ, ψ, θ). For navigation three tyros and three accelerometers, each pair in x, y, z axes are required. If the negotiations with the National Laboratories, IITs and University become successful, we will be able to design Bio-mimicking types of MAVs. Similar models can be suggested for other insects for which the basic data is available for 5 insects, 5 birds and 2 bats with us



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Chapter 13
Navigation—A General Overview

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Abstract Navigation is the method of determining location, route, and distance travelled by humans, birds, aquatic animals, insects and transport vehicles belong to surface or water or air. Animals and birds are using various types of natural methods for orientation and navigation from one place to another place. Navigation in animals is mainly controlled and influenced by the internal and external factors. Migrating Birds, which travel long distances and return back to their original place, are using different natural compass systems and maps for orientation and identifying the places during the migration. The natural compass systems like Sun, Stars, Moon and Geomagnetic are explained in this chapter. The mechanisms of maps used by the birds or animals are olfactory, mosaic, cognitive, geo-magnetic and gradient etc. Map systems play the crucial role in the life of animals for their daily requirements. Animals and birds will face challenges for migration or navigation during inclement weather. Infra sound vibrations are also used by the birds as well as sea animals for long distance travelling. Sense organs play a vital role in animal migration and navigation. The behavioral experiments or neuroanatomical studies are required to study the migration and orientation in labs. Navigational aids used by human beings in early stage of navigation are compass, nautical charts, sextant and chronometers etc. Modern day's navigation systems are Global Navigational Satellite System (GNSS), Inertial Navigation System (INS), Radio Detection and Ranging (RADAR), Sound Navigation and Ranging (SONAR), Long-Range Navigation (Loran), Light Detection and Ranging (LIDAR) and Instrument/Microwave Landing Systems (ILS/MLS). These navigational aids are used in missiles, rocket launching pads, ships, submarines, airplanes, trains, land vehicles, autonomous vehicles, robots etc. Few navigation systems like

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INS, GNSS, RADAR, ILS /MLS and LIDAR are discussed briefly. Micro Electro Mechanical System (MEMS) technology is a fast growing semiconductor technology with their inherent advantages like small size, low power consumption and very cost effective. Heavy mechanical components like accelerometers and gyroscopes of the inertial measurement units are replaced with MEMS based devices. How the MEMS are helpful to design the navigation for Micro Areal Vehicles (MAVs) is explained briefly. Integration of low cost and light weight MEMS based navigation devices with other navigation systems will address the challenges in the navigation of MAVs to resemble the natural fliers.

Keywords Migration · Navigation · Birds and insects navigation · Bionavigation · Bio-mimicking navigation · GNSS · INS · ILS/MLS · MAVs · MEMS

Navigation—A General Overview

Navigation is the art of directing a vehicle such as an aircraft or a person from one place to another place. Many methods and models like stellar, solar, magnetic, olfactory and other orientation and navigation systems are relatively well known in biological fliers. Orientation using Electromagnetic induction is common in some fishes, aquatic mammals (whales and dolphins) and other biological fliers. However, each type of model that has been proposed, has its theoretical and observational basis and its own serious limitations due to Nano-technological implications. Further studies[1] have revealed that multiple mechanisms appear to exist in nature, which also adds to the complexity in understanding the navigation problems.

In the early stages of navigation, various instruments like compass, clock, theodolite and chronometers were used. Many methods for navigation and orientation, including the sensors for aerial vehicles are being proposed in the scientific literature. It is well known that pigeons and some other birds use the land marks and magnetic orientation during migration and home coming. If the weather conditions are not favorable and more so during night, visual piloting by using land marks during prolonged migration may be a challenging task. Stellar navigation using the location of bright stars, seems more common in some nocturnal migrant fliers such as Song birds. However, this may not be feasible for many non-avian migrating fliers [1]. Navigation is mainly controlled by animal's internal environment (Physiological and Hormonal status), influenced by genetically and external environmental factors viz., fast sensory feedback systems which in turn are controlled by various segments of the brain as may be required in different phylogeny of animals. Social relationships in migratory swarms and collision avoidance in certain groups of fliers, also influence the long distance migration and navigation to a certain extent. It is rather difficult to separate migration and navigation in natural fliers. Prof. N. Srinivasan from Australian National University has shown how honeybees use vision for

[1] This is a general article where fundamental aspects of navigation have been mentioned and only a few references have been quoted.

landing, takeoff and avoid obstacles. Barrows et al. [2], have discussed perception of depth and optical flow. Optical flow helps in visual navigation in detecting horizon. Insect ocelli give a simple system of optical flow detection [3].

As compared to the navigation methods used by biological fliers, many types of artificial navigation systems are available in man-made fliers such as aero-planes, missiles, ships, submarines and surface transport systems. However, complex biological feedback systems with sense organs and brain in natural fliers and other migratory animals for navigation are not well understood and hence a big challenge for replication designs.

Microchiropteran bats which make use of echo-location have inspired the scientists to invent radar and a deeper understanding of ultrasonic waves. Recently many advances came in radar technology. We are able to model the terrain using Synthetic Aperture Radar (SAR) and Multiple Input and Multiple Output (MIMO) systems by various types of radars. Radar entomology helps us in understanding insect navigation, insect flight and more about migration. Bio-navigation systems have taken millions of years, through a process of natural selection and adaptation and hence they are much more superior and complex in structure and function, as compared to man-made systems. The art of flying and science of navigation in insects, birds and bats are quite complex and not fully understood. The man-made vehicles and their navigational procedures on the other hand are better amenable for analysis and further improvements.

First, a brief overview of different methods or techniques of manmade navigational aids, which are in use by present day scientists are explained in this chapter. Later the navigational methods used by the biological fliers are commented upon briefly. Finally the article concludes with the discussion on possibility of using Micro Electro-Mechanical Systems (MEMS) for navigation in Micro Aerial Vehicles (MAVs) and Unmanned Aerial Vehicles (UAVs).

Navigational Methods and Techniques Used by Present Day Scientists

Many types of artificial navigational aids are designed for satellites, aeroplanes, missiles, ships, submarines and surface transport vehicles. Some of the popular navigational systems are explained very briefly.

Inertial Navigation System (INS)

The basic working principle of INS follows from Newton's laws of motion. INS is a Dead Reckoning technique of navigation, which uses the measurements of accelerometers and gyroscopes. These two instruments fixed to the object are used to track the position, velocity and orientation of the object with respect to a starting point. INS consists of inertial measurement unit (IMU) and a navigation processor. IMU consists of three orthogonally placed gyroscopes to measure angular rate and three orthogonally placed accelerometers to measure the linear acceleration. INS gives the position without taking any external signals. Hence it is called self-contained system and it is not influenced by external factors [4]. Inertial navigation system has a wide range of applications in aircrafts, missiles, guidance systems, launch vehicles, space-crafts, submarines, ships, intelligent transport system and autonomous navigation.

INS usually fall into the following two categories of implementation:

a. Gimbaled or stable platform system
b. Strapdown system.

a. **Gimbaled or Stable platform system**

INS technology includes inertial sensors mounted on stable platforms. These are mechanically isolated with rotational motion of the moving vehicle by gimbals. Gimbal is a rigid frame having rotational bearings for isolating a frame from another frame due to rotations, about bearing axes (pitch, roll and yaw). Such arrangement helps it to rotate freely in all the three axes. A minimum of three gimbals are needed to isolate the subsystems from the rotations of the vehicle about three axes. In INS, the gimbals are mounted one inside the other. The torque servos and gimbals are helpful in nullifying the rotation of stable platform where the inertial sensors are placed as shown in Fig. 13.1. Gimbal platform systems are used in order to estimate the accurate navigational data of ships and submarines.

b. **Strapdown system**

In the Strapdown system inertial sensors are mounted or attached to the host vehicle as shown in Fig. 13.2. In place of gimbals, computers are used to simulate frame transformation and calculate position, velocity and attitude of the moving vehicle [5]. Strapdown systems are small in size, low cost, reliable, flexible and low power consumption compared with stable platform. The Strapdown Inertial Navigation Systems (SINS) are becoming more popular with their advantages. Different types of accelerometers and gyroscopes like Fiber Optic Gyroscopes (FOG) and Ring Laser Gyroscopes (RLG) are available to use in strapdown navigation systems.

Accelerometers

Accelerometers are used to measure the acceleration in three directions. Accelerometers can broadly be classified as either a mechanical or a solid-state device. In this section these two types of accelerometers are described including MEMS accelerometers.

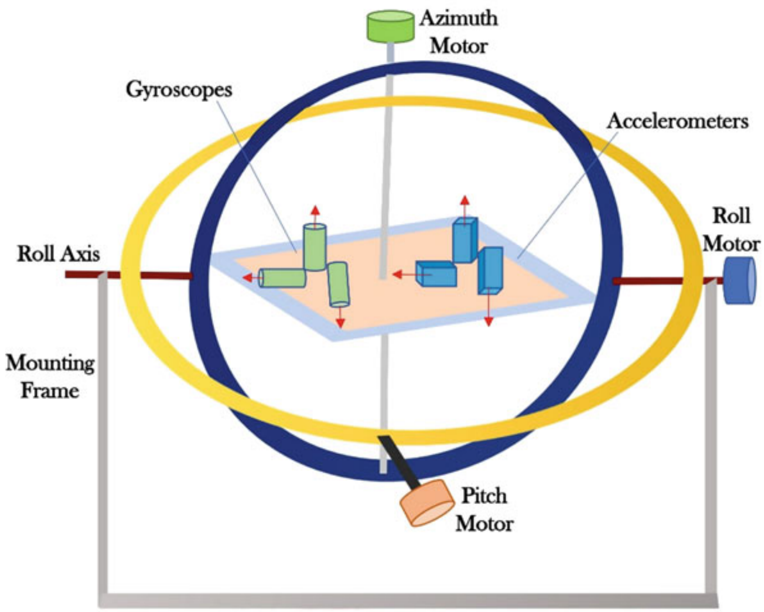

Fig. 13.1 Inertial platform of gimbals

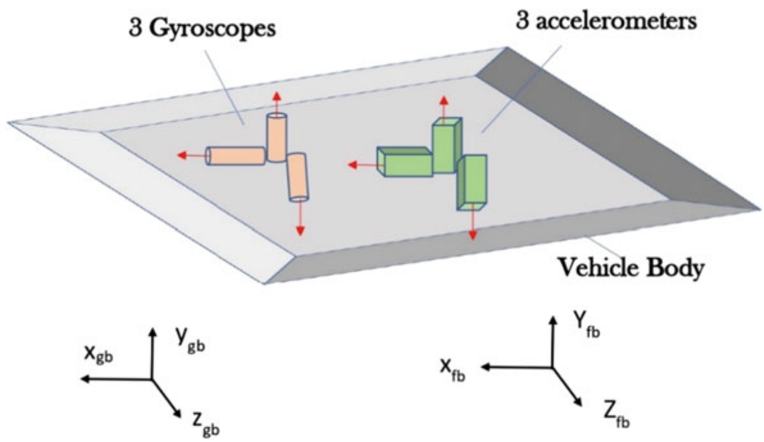

Fig. 13.2 Strapdown inertial navigation system

a. **Mechanical Accelerometer** consists of a mass suspended by springs, as shown in Fig. 13.3. The displacement of the mass is measured using the displacement, giving a signal that is proportional to the force F, and acting on the mass in the direction of the input axis. Newton's Second Law $F = ma$ is used to calculate the acceleration.

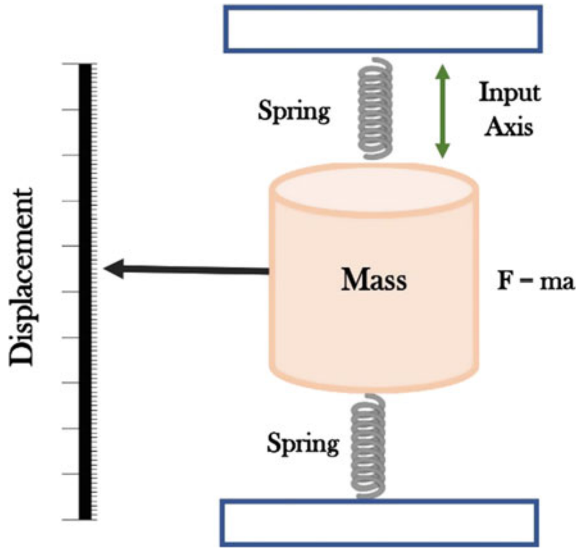

Fig. 13.3 Mechanical accelerometer

b. **Solid-State Accelerometers** are intended to positioning of robot or platform. It is a self-contained system, small in size and low cost. These are divided into several sub-groups, and they are vibratory, silicon, surface vocal wave and quartz devices. Surface Acoustic Wave (SAW) accelerometer is one of the examples of solid state accelerometers. It consists of resonators on a cantilever beam, resonates at a specific frequency as shown in Fig. 13.4. The beam at one end is attached with mass, it moves freely, and other end is stiffly attached to the case. The beam bends, when the force is applied to the mass. The frequency of resonators changes accordingly which is proportional to the acceleration.

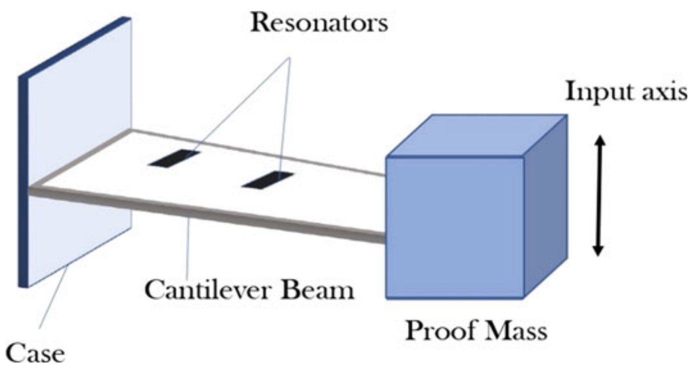

Fig. 13.4 Solid-state accelerometer

c. **Micro-machined silicon accelerometers** consists of two parts, sensors and electronic interface. Both play crucial role in the performance of the accelerometers. These are also called as MEMS accelerometers. MEMS accelerometers are mainly two types. Mechanical accelerometers with MEMS. The second type of accelerometers measures the frequency change in vibrating element due to the change in tension called SAW accelerometers. MEMS accelerometers will have light weight and small size and also takes less power.

Gyroscopes

Three gyroscopes are used to measure the angular rate of the object in three orthogonal axes. Mechanical gyroscopes with gimbals have a lot of friction. The high precision bearings and good quality lubricants are used to reduce friction. Their cost is also very high. However, they do take some time to warm up. Most of these challenges of mechanical systems have been removed in the modern inertial systems with introduction of strapdown systems. The inertial sensors are rigidly attached to the body of vehicle i.e. sensors are strapped down to the body. Different types of gyroscopes like Fiber Optic Gyroscopes (FOG), Ring Laser Gyroscopes (RLG) and MEMS based gyroscopes are available to use in strapdown navigational systems.

a. **Fiber Optic Gyroscope (FOG)** measures the angular velocity with the interference of light. FOG consists of light source and large optical fiber coil. The light beam from light source split into two beams, and they propagate simultaneously along the optical fiber cable in the opposite directions as shown in Fig. 13.5. When the sensor experience a rotation, the beam propagation in the same direction of rotation will travel longer path or distance as compared to the beam propagating in the opposite direction as shown in Fig. 13.6. This is known as Sagnac effect. Here the phase or frequency difference induced between two waves due to the Sagnac effect is proportional to the angular velocity. The frequency difference is measured in a laser resonator and phase difference is measured in the Interferometric Fiber Optic Gyroscope (IFOG). The accuracy

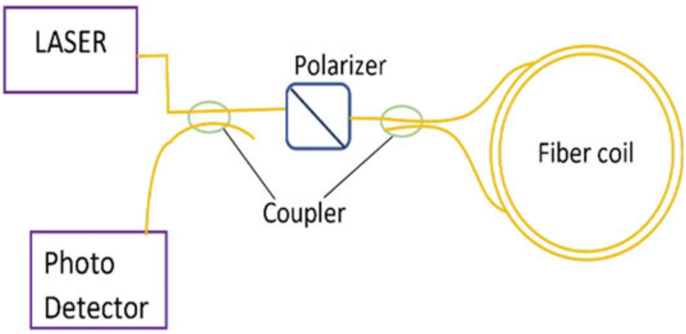

Fig. 13.5 Fiber Optic Gyroscope (FOG)

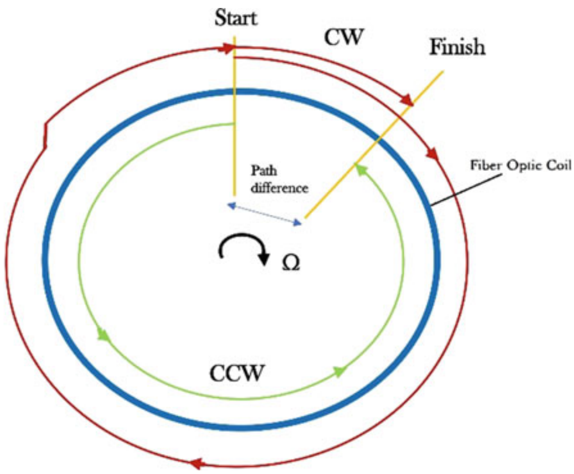

Fig. 13.6 Principle of Sagnac effect

of optical gyroscope depends on the intensity of light and size of the instrument [6]. The salient features of these gyroscopes are less power consumption with light weight, low cost, reliability and wide dynamic range.

b. **Ring Laser Gyroscopes (RLG)** is also working based on the Sagnac effect. RLG uses laser beam and mirrors rather than light and optical fiber coil as compared to the FOG as shown in Fig. 13.7. The laser beam separated as a two beams, and these beams travel in opposite directions in the mirror loop.

One travels in clock wise (CW) direction, and other travels in Counter Clock Wise (CCW) direction. These two beams are recombined and given to the detector.

The detector will find the path difference between two beams. If the path difference of the two beams are same, then it means there is no rotation in the device. If rotation occurs, there will be a path difference between two beams and result in a net phase difference and destructive interference. The amplitude changing in accordance to the phase shift, therefore the amplitude outcome is a measurement of the rotation rate. The main advantage of RLG is no moving coil means no friction, hence there is no inherent drift, compact in size, light weight and virtually everlasting device.

c. **MEMS Gyroscopes**: MEMS based inertial sensor technology is a fast growing and became a ubiquitous with their adoption in many applications like smart phones, gaming systems, TV remotes, wearable sensors and in MAVs for navigation purpose. The MEMS sensors are manufactured with very small in size and light weight using the latest advanced technologies. MEMS based gyroscope operates on the principle of Coriolis effect, which states that in a reference frame, an object with mass m, rotating with angular velocity ω and velocity V which experience a force Fc.

$$Fc = -2m(\omega x V) \tag{13.1}$$

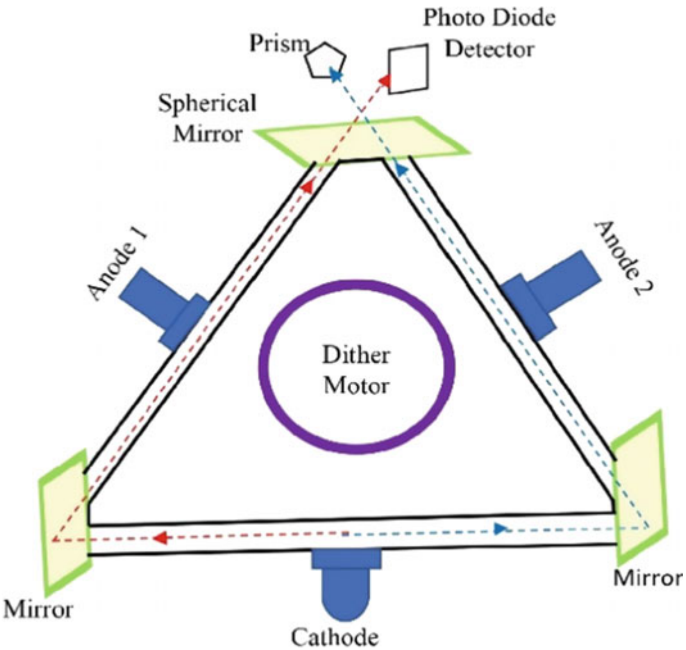

Fig. 13.7 Ring Laser Gyroscope (RLG)

MEMS based gyroscopes contain vibrating elements for measuring Coriolis effects. Many geometries are existing with vibrating elements. The simplest geometry consists of a single mass, and vibrates along a driven axis. Secondary vibration is generated along the perpendicular spin axis, when the gyroscope is rotated. With this secondary rotation, angular velocity can be calculated.

The accuracy of MEMS sensors do not match with the accuracy of optical devices. The advantages of MEMS inertial sensors are as follows:

- Less power consumption
- Rugged structure
- Small size and Low weight
- Small start-up time
- Low cost
- High reliability
- Less maintenance Compatible

The main drawback of INS is the deterioration of accuracy with time. The accuracy depends on the type and quality of IMUs used for navigation.

Global Navigation Satellite System (GNSS)

GNSS is working based on the signals broadcasted by the satellites. GPS, GLONASS, Galileo and BeiDou are independent global navigation systems, and each one of them can be used independently to find out the coordinates of receiver globally anywhere and at any time. The GNSS system functions on the basic principle of trilateration. If the distance is known from three known points, we can find the location of unknown point in the space [7]. GNSS will use the satellites for known positions. The satellites are moving as per the Kepler's laws. Thus we are able to find out the position of the satellite at the given time, using Keplar's parameters called ephemeris, transmitted by all the satellites, which are in the view to receiver. Then the receiver will calculate the time difference between the transmitted signal from the satellite and received signal in the receiver. The time difference multiplied with the velocity of light will give the distance between the respective satellites and receiver. If three satellites are visible to the receiver, we can compute the positions of the receiver. The clocks at the satellites are synchronized up to a Nano-second accuracy. However, the clock at the receiver end is not synchronized with the clocks at satellites. This difference in synchronization between the clocks at satellites and receiver is known as bias, an unknown parameter. So, four visible satellites are required to find out four unknowns including clock bias. The time difference can be calculated using principles of signal processing.

Thus we have the following four equations for unknown variables.

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = (d_1 + b)^2 = \rho_1^2 \tag{13.2}$$

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = (d_2 + b)^2 = \rho_2^2 \tag{13.3}$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = (d_3 + d)^2 = \rho_3^2 \tag{13.4}$$

$$(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 = (d_4 + d)^2 = \rho_4^2 \tag{13.5}$$

Here (x, y, z) are the coordinates of the unknown receiver and b is bias.

These independent GNSS systems will consist of three segments as shown in Fig. 13.7b which are called as

(a) Space Segment
(b) Control Segment and
(c) User Segment

Space segment includes satellites, which are transmitting signals towards the earth as shown in Fig. 13.8. Control segment consists of reference stations and master control station to track and model the orbital parameters of the motion of the satellites. Ground antennas at earth station will uplink these model parameters to the satellites.

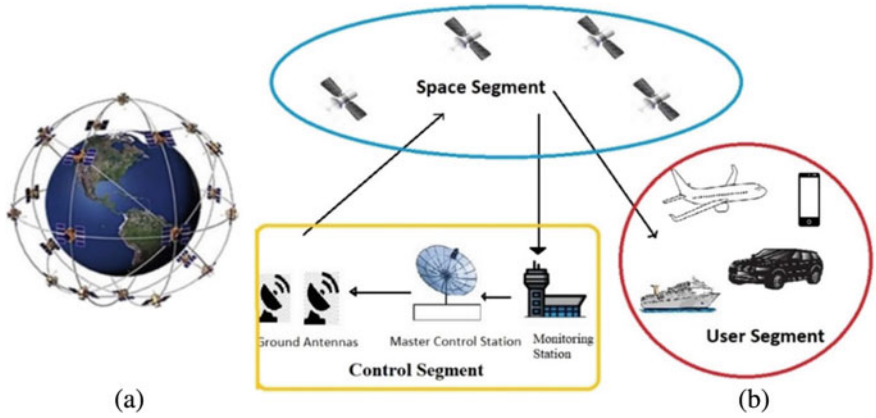

Fig. 13.8 **a** GNSS satellite constellations and **b** GNSS segments

User segment contains the GNSS receivers to compute the position using the signals received from the satellites. The signals transmitted by the GNSS satellites use the CDMA and spread spectrum principles. GNSS has different signals for military and civilian users.

The assumption that "velocity of light is constant" and "travel in straight line" gives some error in the computation of time difference due to refraction of signals in the Tropospheric and Ionosphere regions, and also due to refraction. These errors are with respect to time and place due to varying medium characteristics. Similarly some other errors due to clock drift, receiver noise etc. will add to the errors in position computation. Hence additional augmentation systems are developed to increase the accuracy of GNSS. NavIC/IRNSS and QZSS are regional satellite navigation systems covering only India and Japan respectively, with limited number of satellites. The main drawback of GNSS for positioning or navigation is interference, multipath and other errors like ionosphere, drift in clocks, loss of signals etc., which degrade the accuracy of the position. Of course GNSS cannot be used in the indoor navigation.

RADAR (Radar)—Radio Detection and Ranging

Radar radiates the energy into space in the form of electromagnetic signals. The properties of radiated electromagnetic energy have made it possible to measure the range or the distance of the object under investigation. When these electromagnetic waves reflected by any object, these signals are received again by radar and calculates the distance between radar and that particular object [8]. Electromagnetic waves travel in the space with the speed of light (300,000 km/s), meaning it maintains a constant speed. Radar measures time difference between the transmitted pulse and reflected pulse. By using the constant speed and time measurements, it permits to determine the distance between radar and reflected objects. Radar is very much used in airplanes, spacecraft's, land vehicles, ships, astronomical bodies and terrain. Generally the electromagnetic wave travels in a straight line, but slightly varies due to the weather and atmospheric conditions in the space. Special antennas are required to receive the reflecting signal in a desired direction. Consequently the radar measures the elevation and azimuth directions of reflected object. All these principles are fundamentally incorporated into the radar system. This allows the estimation of the direction, height, distance and the position from the reflecting objects. Radar operates with microwave and ultra-high frequency signals.

The advantages of radar as compared to normal visual observations:

- Radar operates in all kinds of weather conditions
- It is capable to operate in any time with a long range
- Radar has wide-range of coverage with high frequency signals
- It is able to penetrate through walls and snow layers also
- Radar can detect moving objects with fairly good resolution and recognition
- Radar Entomology covers scientific study of insect navigation and insect flight
- Whole hemisphere can be observed by radar.

However, radar is used to find the position of other objects also. The main application areas of radar for navigation is Military, Space, Air traffic control, Remote sensing and Ground traffic control etc. However, nowadays radars are also used in biomedical instruments and mining.

Radar Entomology has played a vital role in understanding insect flight and also pest and migratory fliers, which attack agricultural fields and other trees in the forest.

Instrument Landing Systems (ILS) and Microwave Landing System (MLS)

For flights, approach phase is more difficult, since some maneuvering is done before final descent. The word approach is used to describe the phase of flight, which immediately precedes the landing. Of course, the landing phase of flight requires highest navigational accuracy, particularly in the vertical direction.

Landing is very critical for flights. Landing is usually designed to be at a 3° descent angle and on a track aligned with the central line of runway. Generally the final descent path starts at 4 NM from threshold and intersects or touches the runway at a point 1000 ft/300 m past the threshold. The pilot will stabilize the aircraft within the straight section of the approach of 4 NM (i.e. almost within 2-min), such that the aircraft will touch the runway with desired 3° decent, airspeed and ground track. The ultimate objective of landing is to land the aircraft safely.

Two types of approaches are used for landing purpose. They are non-precision approach and precision approach. Only horizontal guidance is provided by non-precision approach. Precision approach provides both horizontal and vertical guidance for landing. Nowadays for precision approach the Instrument Landing System (ILS), Microwave Landing System (MLS) and Differential GPS (both Local and Wide Area) are used.

The ILS is an instrument based technique to guide the airplane for safe landing in precision approach method. It uses two directional radio frequency (RF) beams to provide both horizontal and vertical guidance to the pilot during an approach to landing. The main components in ILS are localizer, glide path and markers. RF signals or are used to provide the horizontal guidance called the localizer (108–112 MHz) and vertical guidance called glide path (329.15–335 MHz) and the track position fixed by the markers. The Distance Measuring Equipment (DME) also installed in some ILS to provide the slant distance to the airplane with respect to ground touch point. Generally the DME is accompanied with the glide path antenna. The localizer antenna array is placed about 1000 ft off the stop end of the runway. It radiates two signals one is at 90 Hz with AM modulated, and other is at 150 Hz. For vertical guidance also, a signal is generated as similar to the horizontal guidance but it rotates at 90°.

The frequency of the signal is in the range of 300 MHz. The glide path antenna array is mounted vertically. The height of this antenna array would be too great to be installed safely near a runway (usually about 1000 ft. from the threshold and 400–500 ft. from the edge of the runway).

Microwave Landing System (MLS) is a precision landing approach. It installed in large airports to provide landing maneuvers in all weather conditions. MLS provides three dimensional navigation guidance; azimuth, elevation and distance for exact decent and alignment of airplane. ILS and MLS will be very much useful during the visibility problem due to fog, rain and aerosol.

Vision and LIDAR Based Navigation

Nowadays vision based navigation is playing a key role in autonomous navigation. In this system, input is taken from the optical sensors like cameras and it is processed in Deep Neural Network (DNN) based systems and produces the control signals to the vehicle. The main role of DNN systems are detection and classification of objects such as estimation of road curvature, obstacle and traffic signs etc. All these tasks are done with very high speed. Then only the autonomous navigation system will take the decision in time.

Light Detection and Ranging (LIDAR) measures the distance and relative angle of target by computing the time of flight with illumination of laser beams. Basic components of LIDAR are laser, scanner and a GNSS receiver. It is extremely suitable for 3D mapping of surrounding environments. Vision and LIDAR working together will detect the surroundings fully and gather the contextual information of surroundings in any weather conditions. The autonomous systems are working safely and smoothly by detecting the obstacles and avoid the collisions with the help of combined vision and LIDAR systems.

Main applications of vision and LIDAR based systems are self-driving cars, autonomous underwater vehicles, unmanned aerial vehicles, micro aerial vehicles, mobile robotics and terrestrial applications.

Navigational Methods Adopted by Natural fliers

Birds migrate to different places during winter and come back to native place after winter. They migrate for several thousands of kilometers and they reach the destination using compass for orientation and maps for identifying the place. Orientation is the capability to maintain a particular direction of compass. Birds are having their own inherent compass systems for migration. If any animal wants to move for long periods of time in a conventional way, they need some compass system.

Migrating birds do not have inborn maps. But, most of the birds will travel and reach to same place for the next year. Procellariiforms are Sea birds, and they fly long-distance in the ocean, to trace the same Island for breeding in the next year. It is assumed that these birds are permanently connecting to that place by frequent circumnavigation of the earth. Winter sites are suitable for breeding of migratory birds.

The methods of study of migration, navigation and orientation require the behavioral experiments, Neuro anatomical studies and combination of both. The behavioral experiments are done by Round Arena in the Lab (by keeping a bird in cage), Radio tagging for the free flying birds and ringing [9].

Various navigational methods followed by natural fliers include the following:

a. Visual Land Marks
b. Star patterns at Night
c. Sun as a Compass
d. Moon Orientation
e. Meteorological Features
f. Geomagnetic Fields and Infra-magnetic Detection
g. Polarized Light
h. Ultra violet Rays
i. Odor/Smell sensory Methods
j. Echo-location in Bats
k. Sound vibrations by hearing

a. **Visual Land Marks**

Navigation with topographical map is called as piloting. Fliers make use of landmarks, mountains and rivers. They remember these features during their migratory flight path. Vision is highly developed except in small bats which depend on echo location. Birds remember previously visited places and navigate those places easily by familiar area map mechanism [10].

b. **Star Patterns at Night**

Nocturnal fliers make use of navigation based on bright star (Stellar) pattern. The large numbers of stars are visible in the sky with different patterns at different times in the night. Probably nocturnal migrants own some form of star patterns for their migration [15]. Indigo buntings are using specific star patterns.

c. **Sun Compass**

The sun compass is related to the flier's internal circadian rhythm. This is more useful for high altitude migration and in arctic region, where the sunlight is continuous and the magnetic directions are not clear. Sun compass is a regular explicitly movement of the sun across the sky. Hence it is time dependent. Solar arch is mainly dependent on the geographic latitude and season. Diurnal migrants are primarily using this method for orientation [11]. Pigeons consider only the azimuth of the Sun and ignore its elevation above the horizon.

d. **Moon Orientation**

This is also common in some nocturnal fliers. Moon compass is the polarization pattern in the sky created by the moon. Insects can use the moon as a compass. Some studies are needed to find out if the variable intensity of light of the moon changing day-to-day is used by the nocturnal fliers.

e. **Meteorological Features**

These involve the detection of wind velocity, pressure, temperature and moisture, which is done in insects by the use of antennae and sensory hairs (Tricho-bothria). Birds and migratory mammals also respond to such meteorological features.

f. **Geomagnetic Field**

Certain microorganisms to mammals have the capacity to detect and react to the earth's magnetic field over a wide range. Migratory species have considerable number of magnetic particles in their body cells. Migrating birds can perceive information based on intensity and direction of the geomagnetic field, and these are transmitted to the brain. Migrating bird's capacity of finding position is at the scale of hundreds and thousands of kilometers. The magneto reception mechanism has been recently proposed to help in navigation and the reactions occur in the eye in the eye of the migrants [See Chap. 15].

g. **Polarized Light**

It consists of electromagnetic waves. The rotation of polarized light along with the sun reveals the North direction. Many insects and birds use the polarized light during the cloudy days.

h. **Ultra-Violet rays Sensing**

Avian fliers use Ultra-Violet (UV) rays to detect the polarization pattern. Birds have capability to recognize near Ultra Violet spectrum. Perception of UV rays by birds is used for prey, food detection, signaling and communication. Most of birds like eagle, hawk, and frugivorous birds etc. are using UV rays for prey.

i. **Odour/Smelling Sensory Method**

It helps in detecting odour. It can be chemical or biological in its origin. Along with vision, this helps in landing, take-off and searching for food and also for facilitating the search for mating (breeding). Moths, Salmon and pigeon are well studied examples for animals which are using smell for orientation in their environment [12].

j. **Echo-location Techniques in Bats**

Echo location in small bats is carried out by ultra-sonic waves ranging from 30,000 to 100,000 Hz. This is a unique evolutionary feature, which makes use of ultra-sonic waves and ears during night. Oil birds are also using this method for navigation, but basic/limited skills are used by the oilbirds.

k. **Sound Vibrations**

Sound vibrations are detected by the ears and the final detection and analysis is done by internal ear and the brain. Infra sound vibrations are used for long distance migrants rather than short distances. Some birds like pigeons are sensitive to hearing low frequency. They use infra sound vibrations for long distance travelling. Monarch butterflies also use them for migration. Sea turtles appear to use infra sound and acoustic waves for long distance travelling across ocean [14].

Many biological fliers, by making use of sense organs, prefer to migrate towards tropical regions for warmth, food and for breeding. Photo periodism plays a significant physiological role in the migration of insects, birds and mammals. The following Table 13.1 will give the orientation and navigation methods used by the migrating fliers, and this information is collected from various sources.

MEMS for MAV Navigation

MEMS is a technology and a methodology used in realizing micro-electronic and mechanical devices. This technology also helps us to design and integrate various components including MEMS for building a complex model or system. Further, space and defense applications are considering the size and cost effective designs for highly focused mission objectives. Most of the mission objectives are based on the total weight of the components and systems developed. Thus, by using MEMS technology, possibility of replacing the heavy and bulky components that are used in space, communications and navigation is quite possible [13]. Not only replacing

Table. 13.1 Orientation and navigation of migrating fliers (Maintain direction towards goal)

Bio-navigation piloting using	
Compass systems	Map systems
(1) Solar compass (time dependent) for orientation (a) Sun movement across the sky (b) Planetarium (fixed sky)—photoperiod is shifted, clock shifting experiments mimicking (c) Sun compass is related to Circadian rhythm (d) Rotation of polarized light (e) Polarized light and its patterns (2) Stellar compass (star pattern) (a) Based on the pattern of constellations and rotation. Bright pattern (b) Northern star-polaris along with sun reveals north direction (3) Moon compass (a) Moon shining is by reflection (b) Emits partially polarized light (c) Moon does not emit its own light (d) The quantum of light received from Moon by earth is variable. Birds have Celestial compass (4) Geo-Magnetic Compass concept is rather (a) Radical-pair mechanism involved in the process of magneto reception	(1) Geo-magnetic map-field (a) Parameters are useful (2) Olfactory map (a) Chemo-smelling (concentration gradient) pheromones (3) Mosaic map—as in insect ommatidium (4) Cognitive map geometric parameters of an area (5) Gradient map concept can be used for navigation across hundreds and thousands of km (6) Infra sound for short distance Landscape structures and sea coast 0.1 to 10 ν (7) Role of Hypothalamus in navigation

but are also useful in terms of improving the performance and durability of these payloads by reducing various forms of losses, which used to be a biggest challenge for the field engineers.

In navigational applications, devices manufactured using MEMS technology are ideal to replace several heavy components and subsystems, viz., gyroscopes, inertial measurement units. Finally, such replacement of these components enables the micro fabrication of MAVs with highly integrated technological adaptations. Navigation along with communication and feedback sensory control systems can be implemented for the design of MAVs using MEMS technology due to low power consumption, high precision and low maintenance.

Extensive work is carried out in worldwide laboratories on the MEMS technology. This lead successfully fabrication of various components in the area of navigational applications as listed below:

a. Inertial Sensors—accelerometers, gyroscopes
b. High Frequency (HF) devices—communication applications
c. Optical sensors—mirrors for photography and video capturing.

A relevant technology based on MEMS uses thermal technology in the heated gas molecules detects acceleration. This principle is fundamentally behind the manufacturing of IC based accelerometer products. Wide range of MEMS based IC accelerometers and tilt sensors are transported to automobile industry and various consumer products every year. Several advantages of these products are given below:

- Immune to vibrations—no measurable resonance
- Virtually indestructible (Very high shock tolerance capacity $\approx$ 50,000 g)
- Hysteresis are undetectable
- No friction
- Excellent zero-g offset stability
- Sensor and electronics integrated onto monolithic IC.

At present, most of the MEMS based gyros and accelerometers with different specifications are available with Analog Devices Inc (ADI). To manufacture and reach the ultimate goal of navigation for MAVs with micro fabricated MEMS, may need to face many challenges. Reliability of MEMS in these applications is to be assessed with temperature burning, G test, vibration tests and other aerodynamic considerations. These tests vary from wafer to wafer, batch to batch and sometimes rely on product.

A top-down approach can be followed to replace the bulky and heavy components by MEMS, but bottom-up approach is needed to apply MEMS based navigational systems at various superior platforms. The successful integration of MEMS with other navigation devices will address the challenges by the double-oriented approach. It guarantees the successful navigation in MAVs.

Primary navigation is done by GNSS, and as and when GNSS is not available or in the emergency, MEMS bases inertial navigation will be used. Of course navigation will be available in all weather conditions by integration of GNSS with MEMS based IMU sensors.

Integrated GNSS and MEMS based navigation with single chip for affordable cost, light weight and size, is very well suitable for MAVs for Accurate and reliable navigation.

Summary

Various navigation methods used by Human being in olden days and present days are described. Nowadays MEMS based Inertial Sensors, Global Navigation Satellite Systems, Radar, ILS/MLS, Vision and LIDAR are used for navigation. All the above mentioned methods are elucidated one by one.

- Inertial sensors are independent systems which give position, velocity and attitude of moving vehicles, used for ships, aircrafts, space crafts and land vehicle applications. Increase in errors with time is the main limitation for INS.
- GNSS is a satellite based positioning systems, and many users are using GNSS for military purpose, transportation, mapping etc. Only useful in the outdoor environment. Ionosphere, atmosphere and interference like jamming and spoofing

the signals will degrade the accuracy or position may not available completely or continuously.

- Radar finds the distance, position and height of the object by reflecting EM waves. Basically radars used for military applications, air traffic control, space applications and remote sensing etc.
- ILS is a landing system for aircrafts by measuring the distance and angle.
- Vision and LIDAR based systems play key role in navigation of autonomous vehicles.

Navigation and migration methods used by birds, animals and insects are described. Migration plays very significant role in the lifestyle of birds and animals. They migrate for prey, food, breeding, mate, communication and signaling etc.

- Birds are using Compass systems for orientation. They are Sun compass, star compass, magnetic compass, moon compass and weather compass.
- Various maps like olfactory, mosaic, cognitive, infrasound, gradient and geomagnetic maps are used for navigation.
- Sense organs of birds and animals are involved for migration and navigation.
- Polarized light, echo location, meteorological features and sensing ultraviolet rays are also used by different animals in different environments.

Role of MEMS technologies in Micro Areal vehicles are conversed. Heavy components are expected to replace with MEMS sensors, with low cost, small size and low power consumption.

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Chapter 14
Wingbeat Frequency Theories—A Mathematical Approach

G. Shailaja and N. Chari

Abstract Eight theories suggested for wingbeat frequency have been reviewed. The wingbeat frequency is related to body mass, wingspan, breadth and other wing parameters (dimensions). GreenWalt used mechanical oscillator theory. He has related frequency, inversely to length of the wing, with an exponent '*n*'. Crawford calculated frequency directly linking to the mass and indirectly to wing swept area. Pennyquick used dimensional analysis method. Newton used differential equations, and mass flow concept. Ellington evaluated frequency linking to aspectratio and C_L in addition to other wing parameters. Norberg [4] linked frequency directly to mass raised to 1/3. In mass flow theory, frequency depends directly on mass and inversely on L and B_{eff}, wingspan loading is a vital factor in insect hovering. Deakin also used dimensional analysis method for insect in hovering. K value is variable in all theories.

Keywords Mass · Wingspan · Effective breadth · Wingswept area · Disc area

Introduction

The flight of a biological flier is due to Wing beat frequency, and during hovering of the flier, the forward velocity is zero. There are several theories to explain the wing beat frequency of biological fliers. Out of these theories, eight have been reviewed for the calculation of Wingbeat frequency of the biological fliers [1]. The mathematical considerations of these reviewed theories are of special interest since this may help in the design of flapping flexib le wing.

The Eight theories on Wingbeat frequency as mentioned are as follows:

1. GreenWalt's Theory (1962)
2. Crawford's Theory (1972)
3. Norberg's Theory (1990)
4. Pennycuick's Theory (1996)

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https://doi.org/10.1007/978-981-16-5184-7_14

5. Ellington's Theory (1999)
6. Newton's Theory
7. Mass Flow Theory (1977, 2015)
8. Deakin's Theory (2010).

Theories

The mathematical basis for the above theories has been considered as below.

1. **GREENWALT'S THEORY (1962)**

Greenwalt [2] in his Mechanical Oscillatory Theory considered biological flier as a mechanical harmonic oscillator and calculated its wingbeat frequency. He framed a differential equation and solved it in terms of frequency ($\boldsymbol{v_h}$) and wing length ($\boldsymbol{l}$) of the flier and accordingly obtained the following formula:

$$\boldsymbol{v_h l^n} = \mathbf{constant}(\boldsymbol{k})$$

where the wing length ($\boldsymbol{l}$) is measured in millimeters. In this analysis, wings of fliers were considered as damped mechanical oscillators.

The exponent 'n' for '$\boldsymbol{l}$' is varying between 1 and 1.25. He showed the product to be a constant with $k = 3540$ (obtained by trial and error method).

2. **CRAWFORD'S THEORY (1972)**

Crawford [3] calculated wingbeat frequency of a flier by considering actual wing swept area ($\boldsymbol{S_w}$) and not the total wing disc area ($\boldsymbol{S_d}$) of the flier. According to him mass of the flier ($\boldsymbol{M_f}$) and wing swept area ($\boldsymbol{S_w}$) are the two factors which mainly affect the frequency of the flier. His formula is as follows:

$$\boldsymbol{\vartheta_h} = \boldsymbol{K} \times \frac{\sqrt{\boldsymbol{M_f}}}{\boldsymbol{S_w}}, \text{ Where } \boldsymbol{K} = \sqrt{\frac{\boldsymbol{g}}{4\boldsymbol{\pi\rho}}} = 252.44$$

$\boldsymbol{M_f}$ = mass of the flier; $\boldsymbol{S_w}$ = wing swept area and is equal to $\left(\frac{\pi}{3}\right) * radius^2$; ρ = density of air and $\boldsymbol{g}$ = acceleration due to gravity.

This formula is applicable to small myogenic fliers such as mosquitoes where $\boldsymbol{\vartheta_h}$ is high (500 and above).

3. **NORBERG'S THEORY (1990)**

Norberg [4] in the book entitled "Zoophysiology" has considered upper and lower side limits for calculating wing beat frequency. For geometrically similar animals, wing beat frequency varies with the (−1/3)rd power of the body mass.

$$f_{w,\,\max} \propto M^{-1/3}$$

Norberg [4] showed Regression Equations for wing morphology and aerodynamic characteristics for various fliers based on available empirical data. Her general formula has also shown relation between body mass and wing span, body mass and wing loading, body mass and aspect ratio which contribute to a better understanding. For studying the wingbeat frequency she has made use of wing span, wing area, wing loading, and aspect ratio. She has calculated the wing beat frequency and expressed it in terms of mass values. Norberg has considered mass of the flier alone for the calculation of wingbeat frequency and assumed that other morphological flight parameters are related to the mass. The formula is applicable to all birds other than Humming birds. Frequency in Norberg's theory is inversely proportional to mass raised to the fractional power (Table 14.1).

Using linear least squares regression lines she fitted power function for the wingbeat frequency with mass of the body alone as

$$\boldsymbol{\nu_h} = 3.98\ \boldsymbol{M}^{-0.27}.$$

The abbreviations used are as below:

M = mass of the flier (in kg) and $\left(M^{-0.27}\right)$ is variable.

However, for Humming birds, the formula is $\boldsymbol{\nu_h} = 1.32\ \boldsymbol{M}^{-0.60}$.

Wing dimensions and flight parameters against body mass of some birds, bats and pterosaurs have been calculated and enlisted by Norberg [4] in the book entitled "Vertebrate flight". The modified table has been enclosed in the present studies (Table 14.2).

4. **PENNYQUICK'S THEORY (1996)**

In determining the wing beat frequencies of fliers, Pennyquick [5] adopted a hybrid method, i.e. use of

(a) Multiple regression analysis and
(b) Dimensional analysis.

By multiple regression analysis he will determine how the frequency depends on variables such as body mass, wing span and wing area. Pennyquick in his dimensional analysis method identified constraints to which a physically valid solution must confirm.

The list of the variables which are likely to influence the frequency are as follows:

Body mass—m
Wing span—b
Wing area—S
Wing moment of inertia—I
Acceleration due to gravity—g
Air density—ρ.

Table 14.1 Comparative account of theories on wing beat frequency

S. No.	Name of theory	Formula	Proportionality constant (K)	Mass (M)	Wing dimensions	Remarks
1	Greenwalt's Theory (1960)	$v_h l^n = 3540$	$n = 1$ to 1.5		l^n	Considering as mechanical oscillator applied damped hormonic oscillator, derived formula for frequency
2	Crawford's Theory (1971)	$v_h = K_c \times \sqrt{\frac{m_f}{S_w}}$	$K_c = \sqrt{\frac{g}{4\pi\rho}} =$ 252	$M_f^{1/2}$	S_w	Wing swift area is taken into account. Disc area is considered, to calculate frequency as in massflow theory. Suitable in calculating frequency of small insects
3	Norberg's Theory (1990)	$v_h = K_{Nr}(m)^{-0.27}$	$K_{Nr=0.19}$ or 0.24	$M^{-0.27}$	L	Norberg related frequency to the Mass raised to the power (−1/3), wing span (L)
4	Pennyquick's Theory (1996)	$v_h = m^{3/8} g^{1/2} b^{-23/24} S^{-1/3} \rho^{-3/8}$ or $v_h = \left(g^{1/2}\rho^{-3/8}\right)\frac{m^{3/8}b^{-23/24}}{s^{-1/3}}$	$K_p = \frac{g^{1/2}}{\rho^{3/8}} = 390$	$M^{3/8}$	$S^{1/3}b^{23/24}$	Adopted dimensional analysis method similar to Deakins

(continued)

Table 14.1 (continued)

S. No.	Name of theory	Formula	Proportionality constant (K)	Mass (M)	Wing dimensions	Remarks
5	Based on Newton's laws	$\upsilon_h = K_n \frac{\sqrt{m}}{A}$ where,$k_n = \frac{g}{2\pi\rho} = 252$	$K_n = \sqrt{\frac{g}{4\pi\rho}} = 252$	$M^{1/2}$	A	Appling 2nd law of motion and taking amplitude of vibrating wing Newton derived the formula for frequency
6	Ellington Theory (1999)	$\upsilon_h = \sqrt{\frac{1}{0.387}} \cdot \sqrt{\frac{m\ Ar}{\phi^2 R^4 C_L}}$ or $\upsilon_h = K_e \sqrt{\frac{m\ Ar}{\phi^2 R^4 C_L}}$	$K_e = \sqrt{\frac{1}{0.387}} = 1.607$	$M^{1/2}$	$\sqrt{A_r}$ & $\sqrt{\frac{1}{\phi^2 R^4 C_L}}$	Related wing beat frequency to the mass. Frequency formula and is extracted to usual form. This involves wing length (R). Aspect ratio, coefficient of lift etc.
7	Mass Flow Theory (1977, 2015)	$\upsilon_h = K' \frac{m_f}{L^2 B_{eff}}$ where $K' = 2086$	$K' = \frac{8g}{K_n \pi\rho} = 2086$	M_f	L^2, B_{eff}	Equating weight of flier to the lift in hovering state, wingbeat frequency is calculated in terms of m_f
8	Deakin's Theory (2010)	$\upsilon_h = K_d \frac{\sqrt{m}}{A}$ where $K_d = 317$	$K_d = k\sqrt{\frac{g}{\rho}} = 317$	$M^{1/2}$	A	Deakin considering square root mass wing area of the flier calculated frequency by dimensional analysis methods

Table 14.2 Wingbeat frequency calculations using Norberg formulae

S. No.	Name of the flier	Mass (M) (kg)	Formula	Freqency (Hz) Est
I	**Birds**	0.020	$3.87\ M^{-0.33}$	–
	Sparrow			
	Parrot	0.022	$3.98\ M^{-0.27}$	–
	Pigeon	0.250		8.5
	Shore bird	0.400	$4.00\ M^{-0.19}$	–
		0.500		–
	Duck	1.000	$5.00\ M^{-0.24}$	–
	H swift	0.0186	$3.87\ M^{-0.33}$	11
		0.0112		to
	H swift	0.0186	$3.98\ M^{-0.27}$	–
		0.0112		13
	Humming bird	0.020	$1.32\ M^{-0.60}$	–
		0.015		–
		0.0112		–
II	**Bats**	0.0075	$3.98\ M^{-0.27}$	4.6
	H speoris Leaf nosed bat			
		0.250		4
		0.400		to
		0.500		8
	Rousettus	0.0070	$3.87\ M^{-0.27}$	7–9
III	**Insects**	0.020	$3.87\ M^{-0.33}$	
	Grass Hopper			15–20
		0.025		
	T. Javanica	0.000857		50~
	Honey Bee	0.0080		250~
	Crysocoris purpurieus	0.0090		90~
	Bambus	0.00017		130~

He proposed the formula

$$f \propto (\mathrm{mg})^{\alpha} b^{\beta} S^{\gamma} I^{\delta} \rho^{\varepsilon} \tag{14.1}$$

I, the moment of inertia depends on body mass and wing span $\mathbf{I} \propto \boldsymbol{mb}^2$.
Thus equation is converted into practical predictive equation for frequency as

$$\boldsymbol{f} = 1.08 \times \left(\boldsymbol{m}^{\frac{3}{8}} \boldsymbol{g}^{\frac{1}{2}} \boldsymbol{b}^{\frac{-23}{24}} \boldsymbol{s}^{\frac{-1}{3}} \boldsymbol{\rho}^{\frac{-3}{8}}\right)$$

where dimensionless multiplier 1.08 came from multiple regression.

Pennyquick's theory is purely based on dimensional analysis. His formula involves different physical parameters raised to different powers and is given by

$$\boldsymbol{\nu_h} = 1.08 \times \left(\boldsymbol{m}^{\frac{3}{8}} \boldsymbol{g}^{\frac{1}{2}} \boldsymbol{b}^{\frac{-23}{24}} \boldsymbol{s}^{\frac{-1}{3}} \boldsymbol{\rho}^{\frac{-3}{8}}\right),$$

where $\boldsymbol{f} = \boldsymbol{\nu_h}$

The abbreviations used are as below:

m = mass of the flier (gm), g = acceleration due to gravity (cm/sec^2)

b = semi-wing span (cm), s = wing area (cm^2) and

ρ = air density (gm/cm^3).

The frequency of the flier is more influenced by the powers of the parameters (m, g, b, s, ρ) evaluated. The values are in good agreement and are close to natural frequency of the fliers. He studied marine birds. The value of k is 252.

5. NEWTON THEORY

In this formula, the frequency of a flier depends directly on square root of mass and indirectly on wing area. Newton's theory is based on mass flow concept. However, larger samples of fliers have to be used for its confirmation. He considered vibration of wings of a flier similar to an equation of motion of second order differential equation, as per Newton's second law of motion of a body or a particle. Newton also solved the equation assuming sine function.

$$\text{The formula is} \boldsymbol{\nu_h} = \frac{\boldsymbol{K}\sqrt{\boldsymbol{m}}}{\boldsymbol{A}},$$

where $\boldsymbol{K} = 252$ and m = mass of the flier, A = wing area.

6. ELLINGTON THEORY (1999)

He studied the kinematic changes with the flight speed of bumblebee [6]. Other insects like 'fruit fly' and 'hawk moth' were also studied. He derived the mass 'm' that can be supported during hovering as

$$\boldsymbol{m} = \frac{0.387\phi^2 \boldsymbol{n}^2 \boldsymbol{R}^4 \boldsymbol{C_L}}{\boldsymbol{A_r}},$$

(This can also be expressed in terms of $\boldsymbol{\nu_h}$)

$$\boldsymbol{\nu_h} = \left(\frac{\boldsymbol{m}\boldsymbol{A_r}}{0.387\phi^2 \boldsymbol{R}^4 \boldsymbol{C_L}}\right)^{1/2},$$

where ϕ is wingbeat amplitude (peak to peak in radians) and

$n = \boldsymbol{\nu_h}$ is strokes/seconds of wingbeat (Hz)

R is wing length (m)
C_L is the coefficient of lift
A_r is aspect ratio of wing
m is mass of insect (kg).

7. MASS FLOW THEORY (1977, 2015)

Amongst all theories Mass Flow Theory suggested by Puranic et al. [7] is more reasonable since observed and experimental results are in good agreement. Chari and Achary et al. considered mathematical aspect, and further this was reviewed by Chari [1]. For sustained flight during hovering, lift must be equal to the body weight. The comparison of basic aerodynamic forces of insects, bats and birds can be the basis for understanding and designing bio-mimicking aerial vehicles with flapping flexible wings.

In mass flow theory frequency of biological flier is based on mass of the flier (M_f), square of the wingspan (L^2) and breadth of the wing (B_{eff}). Here all the four dynamical forces namely weight and lift, thrust and drag are taken into account. The rate of flow of air ($\frac{\mathrm{dm}}{\mathrm{dt}}$) displaced by the flier is mathematically related to frequency. The constant of proportionality is shown as 2086. In this Mass flow theory the constant 2086 is calculated by empirical formula and has been verified experimentally. The calculated and observed frequencies are in good agreement.

The formula for wingbeat frequency is

$$\upsilon_h = \frac{K^1 M_f}{L^2 B_{eff}}$$

where $K' = 2086$, M_f = mass of the flier,

L = wing span, B_{eff} = maximum wing breadth.

The value of K' is determined experimentally by drawing a log–log graph of $M_f \nu_{\text{h}}$ $\nu_0 L^2 B_{eff}$ and the graph is a straight line. In brief, the equation can be summarized as follows:

$$\boldsymbol{M_f g} = \boldsymbol{K S_d B_{\text{eff}} \rho \nu_h}/2, \text{ where } \boldsymbol{S_d} = \frac{\boldsymbol{L}^2}{4}$$

$$\text{Finally } \boldsymbol{\nu_h} = \left(\frac{8\boldsymbol{g}}{\boldsymbol{K}}\right)\frac{\boldsymbol{M_f}}{\boldsymbol{L}^2\boldsymbol{B_{eff}}}$$

$$\begin{aligned}\text{Wing span loading} &= \frac{\text{Wing loading}}{\text{Aspect ratio}}\\ &= \frac{M/A}{L^2/A}\\ &= \frac{M}{L^2}\end{aligned}$$

Wing span loading is an important aerodynamic and bio-aerodynamic flight parameter in comparative studies.

8. DEAKIN'S THEORY (2010)

Deakin's theory [8] is also based on dimensional analysis. Deakin derived formula for wing beat frequency similar to Newton's formula. But he adopted dimensional method similar to that of Pennycuick. It can be seen that the constant (317) evaluated by Deakin is slightly higher than that of Newton. He worked on several species of insects having typical mass, wing area and wing beat frequencies. He used large samples of insects for conformation. Deakin developed a formula for wing beat frequency of insects considering the "Buckingham Pi Theorem", $f(\pi_2, \pi_3) = 0$ and writing the frequency as

$$\boldsymbol{\nu_h} \propto \boldsymbol{g}^{1/2}\boldsymbol{A}^{-1/4}\boldsymbol{f}(\pi_3) \propto \boldsymbol{g}^{1/2}\boldsymbol{A}^{-1/4}\boldsymbol{f}(\boldsymbol{\rho}\boldsymbol{A}^{1/2}/\mathbf{m})$$

Function $f(\pi_3)$ maybe expanded by means of Frobenius series α.

$$f(\pi_3) = k\pi_2^{-\alpha}(1 + \alpha_1\pi_1 + \alpha_2\pi_2^2 + \cdots),$$

where k and α are dimensionless constants, i.e. pure numbers.

Power is assigned with negative sign for convenience and also as is small, neglecting terms beyond 1, the frequency can be written as

$$\nu_h = kg^{1/2}A^{-1/4}f\left(\rho^{-\alpha}A^{-(3/2)\alpha}/m^{-\alpha}\right)$$

$$\nu_h = kg^{1/2}\rho^{-\alpha}m^{\alpha}A^{-(3/2)\alpha-(1/4)} \tag{14.2}$$

$$\nu_h = Km^{\alpha}A^{-\beta} \tag{14.3}$$

where $K = k\ g^{1/2}\rho^{-\alpha}$ is considered as another constant.

By solving we get $\alpha = 1/2$, $\beta = 1$ and substituting these values in (14.2)

$$\nu_h = k(g/\rho)^{1/2}(m^{1/2}/A) \tag{14.4}$$

Or

$$\nu_h = \frac{K\sqrt{m}}{A}$$

where $K = 317$

m = mass of the flier

A = wing area.

This theory has been applied for calculating the wingbeat frequency of insects.

Summary

- By reviewing the eight theories the different mathematical formulae are suggested for wing beat frequency (ν_h) of the biological flyers and are tabulated.
- Different authors adopted different mathematical methods to relate ν_h to different physical parameters of the flyer.
- Green Walt related frequency inversely to length of the wing with an exponent '*n*'.
- Crawford calculated ν_h directly linking to mass and indirectly to wing swift area.
- Norberg linked frequency directly to the mass raised to $-1/3$.
- Penny quick derived ν_h formula by dimensional analysis method.
- Newton solved differential equation of motion and showed that the ν_h directly proportional to the mass of flyer and inversely to the wing area.
- Ellington evaluated ν_h linking to aspect ratio and coefficient of lift in addition to other usual wing dimensions.
- In mass flow theory, Chari et al. showed that wingbeat frequency directly depends on effective mass and inversely on wing length and effective wing breadth.
- Deakin also by dimensional analysis method related wingbeat frequency to the mass of the flyer directly to the wing area inversely.

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Chapter 15
Comments on Bio-physics of Insect Flight (Present and Future)

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Abstract In this last chapter, the recent studies have been summarized and the probable future studies are discussed. Detailed flight study of parameter data has to be collected and stored for biomimicking designs of aerial vehicles and flapping flexible wings. This study needs a common platform of biologists, physicists, biochemists, mathematicians, aerodynamic scientists, engineers from nanotechnology, MEMS and Bionavigation experts. Biomimicking Navigation Methods for MAVs should be explored with minimum weight and small size. Future magnetoreception and Radical pair reaction studies (RPRM) may help in understanding the secrets of migration.

Keywords Electron transfer · Magnetoreception · RPRM · Cryptochromes · Bionavigation

Present Study

Flight of biological flier in nature is of special interest since it involves basically morphological flight parameters, flight muscles and wing movements for developing aerodynamic forces such as Lift, Thrust and Drag. The biological flight is mainly due to flapping flexible wings with elastic fulcrum which contribute for rotatory motion and a notable variable figure of "8" at the wing tip for development of aerodynamic forces. Figure of '8' helps directly in understanding wing motion having powerful down stroke and a recovery upstroke and associated forces. The flapping flexible wing of a flier develops all the aerodynamic forces together in contrast to rigid fixed wing of an aeroplane. Chitin as a polysaccharide amine and Resilin as an elastic protein polymer (4λ), at the wing base play important role in developing variable

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wing beat frequencies in Neurogenic and Myogenic insect fliers having different frequency range.

During the movement of a flier the aerodynamic forces such as lift, thrust and drag (induced drag) involve their coefficients. *L*/*D* ratio indicates flight efficiency and endurance in migratory flight. They in turn involve mass, wing dimensions, displacement of air and density.

Reynolds number is variable in different groups of biological fliers as compared to an aeroplane. Reynold number goes on increasing in insects, birds, bats and aeroplanes with increase in velocity. Reynolds number can also be interpreted as a ratio of total momentum transfer to molecular momentum transfer which remains to be elucidated fully. Various lift enhancing mechanisms in insects have been reviewed. Formation of Leading Edge Vortex (LEV) is a general flow phenomenon in flapping flexible wings of insects. In an aeroplane the Angle Of Attack (AOA) for stall is about 16°, however, in insects the stall angle is above 60°. This helps in prolonged manoeuverability and recovery during prestall period and prevents serious accident. Leading edge vortices contribute to delayed stall which is highly significant in relation to C_L and C_D calculations. Formation of LEV is a general flow feature in flapping wings having Reynolds number of 10^4 or less and this knowledge helps in developing flapping flexible wing for MAVs.

The Naiver Stoke's equation in its non-dimensional form describes how the velocity, pressure and density of moving fluid are related to each other. Hence it comes out to be a useful phenomenon to understand insect flight under various dimensions. The equation is non-dimensional one [1].

Moment of Inertia of the moving wing is calculated by strip analysis method. However, strip number for the first time has been plotted against strip wing loading, which gives the best possible information for a flapping flexible moving wing. A 3-D study will help in the design of flexible membranous wings in MAVs. Moment of inertia and effective radius of gyration have been calculated for soap-nut bug. The M.I and mutilation study during hovering help in understanding aerodynamic forces in a moving wing. Total energy of the insect and M.I of the wing are calculated. MI study helps in determing torque needed for angular acceleration and for 3D movements matrix and torque are essential.

The wing morphology suitable for insect flight is discussed by the authors in greater detail. Wingbeat frequencies of insects, forward velocity and aerodynamic flight parameters lift, thrust and drag along with certain additional derived flight parameters such as wing span loading are elucidated. Insect wings are membranous outgrowths of exoskeleton chitin originating from pleuron that allows the insects to fly. The textural composition of wings and geometry are suitable for ecological adaptability of the species.

Various theories of wingbeat frequency and their importance in hovering flight of insects have been discussed in detail. Wingbeat frequency of some common insects have been recorded and calculated. Fourier analysis of bioacoustic sound has been carried out in our bio physics laboratory at Nizam college, O.U, Hyderabad. Aerodynamically during hovering lift force must be sufficient to balance the total weight of the flier, while forward velocity being zero. Wing beat frequency in hovering flight is related to rate of mass flow of air, displaced by the wings of the flyer while the tip of the wing of the flyer traces a figure of'8'. Aerodynamically wingbeat frequency plays the prominent role in insect flight. This in turn is linked to moment of inertia. A detailed discussion of moment of inertia and their significance have been explained.

Chintinous membrane and analogous materials along with their chemical compositions are given in Chap. 8. Chitin is known as a most renewable biopolymer in the formation of the body of an insect having commercial importance. Resilin is a very high elastic material useful for wing beat frequency of the insect. Analogous materials like silk and spider fiber and their importance is also discussed. Spider silk is rather bullet proof and can be of great importance in defence and in the design of bullet proof jackets.

Aeroelasticity is a combination of physics and engineering, relating to inertial, elastic and aerodynamic forces involved in insect flight. The aeroelastic phenomena are required basically in designing and developing microair vehicles. The aeroelastic properties of analogous materials studied here need further investigation.

Migration and Navigation of insects, especially Locust and Monarch butterfly have been discussed in some detail. There will be no aerial migration without Navigation.

The Navigation and orientation are due to Radical pair reaction mechanism of Magneto reception in the eye of the flier [2]. Sense organs play a vital role in migration, orientation and navigation. Solar, stellar and geomagnetic compasses help in this process.

Tables about Migration and Bionavigation have been enclosed for information and future guidance in respective chapters.

The design and development of bio mimicking vehicle is the main issue. The design of MAVs is linked to Micro-Electro Mechanical Systems (MEMS), and the production of MEMS is an open challenge for Semiconductor Technology. A brief account of these MAVs and MEMS is also given. The bio-physical and aerodynamical information provided in this book may be exploited in designing and development of bio mimicking small aereal vehicles with flapping flexible wings. Wing and body parameters like wing dimensions, υ_h, wing loading, wing span loading, aspect ratio and other aero dynamical forces can be very much useful in such designs.

Future Study

Information available in the literature for the design of bio mimicking MAVs and flapping flexible wings is rather scanty. The flight data base of insects, birds and bats has to be classified and stored for future research work at global level. Bio physics of insect flight is an interdisciplinary approach, depending on the cooperative contributions of biophysicists, physicists, biochemists, mathematicians, aerodynamic scientists and engineers from nanotechnology. This needs a common platform where the above scientists meet and discuss at national and international levels once in two years.

Migration and Bio-Navigation are the natural phenomena, and the studies are going on for more than fifty years to understand these phenomena. Migration depends on solar, stellar and geomagnetic compasses. The receivers for these compasses, related maps and their functioning responses in the body of flier remain to be further investigated.

Atom an ultimate constituent particle of matter is having central positive core called nucleus composed of neutrons and protons. Outside the nucleus the negatively charged electrons are revolving in discrete energy levels provided by the nucleus. The revolving electrons occupying the energy levels by satisfying different quantum conditions/levels available around the nucleus. The revolving outer most electrons are responsible for chemical reactions in biomolecules (RPRM) as mentioned below.

Any moving charged particle gives rise for magnetism. The orbital and spin motions of electrons can give rise for magnetism. If paired electrons are there in the outer most energy level the atom is magnetically neutral. On the other hand the presence of unpaired electron always produces magnetism, as observed in paramagnetic materials and Radical Paired Reaction Mechanism (RPRM) as reported in recent biological studies.

RPRM radicals are having unpaired electrons in their outer most energy levels. Obviously these electrons exhibit magnetic properties. The magnetism thus developed is too small and is of the order of a few micro tesla (μT) and may work as a magnetic compass in the eye of a migrant bird as reported in recent literature.

This magnetic compass thus developed in the eye of the navigating biological flier can interact with the magnetic field of Earth and may help in orientation and Bionavigation. These unpaired electrons as mentioned above develop spin and which can be parallel and antiparallel. A simplified table for Radical Pair Reaction Mechanism (RPRM) study has been prepared after referring large number of recent references as given in appendix.

Migrating fliers for Bio-Navigation make use of light induced radical pair reaction and their intermediates, which involves coherent spin development of two electrons. This leads to the consideration of quantum effects in the body of biological flier [2] as abridged below (Fig. 15.1).

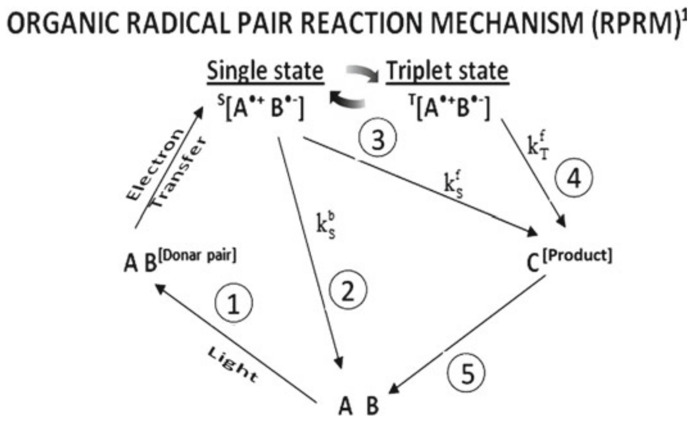

Fig. 15.1 The RPRM appears to operate in Cryptocrome Flavoproteins in the retina of Eye during Navigation (from many sources)

Conclusions

Current evidence strongly suggests that long distance migration has a light-dependent magnetic-compass sensor located in their eyes. The quantum spin dynamics of photo induced radical pairs probably generated in cryptochromes to help in bio navigation which needs future study.

By presenting and explaining the principles of the Radical Pair Reaction Mechanism, we are supporting RPRM to enable migratory fliers to sense the direction of the Earth's magnetic field which is very weak and variable. Multidisciplinary approaches involving quantum physics, biochemistry, computer simulation, mathematical modeling and quantum biology may help in solving this mystery in the days to come.

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