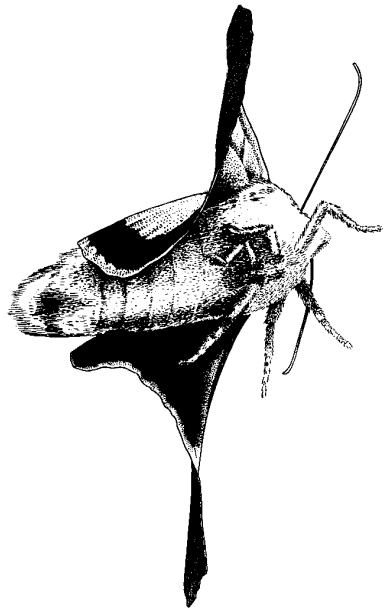
Insect Flight Mechanisms: Anatomy and Kinematics

Carl R. Knospe
Associate Professor
Mechanical and Aerospace Engineering
University of Virginia

Fall 1998

Overview

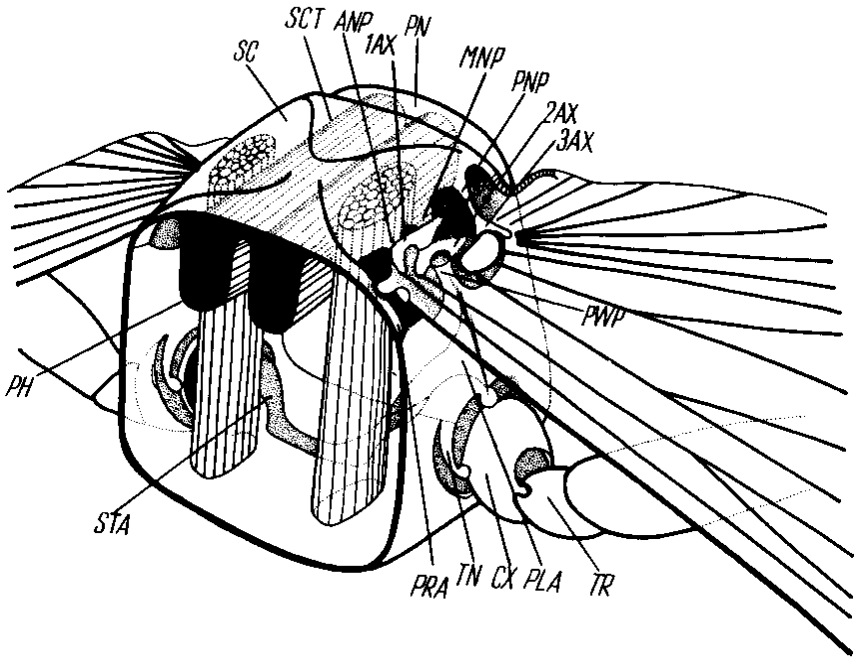
- highly evolved and complex biomechanical system
- all locomotion originates from the insect's thorax, specifically the pterothorax.
- power produced by muscles is transmitted to the wing via the complex interactions of hardened parts of the skeleton



Pterothorax

The pterothorax can be divided into the
- tergum (back)
- pleura (sides)
- sternum (belly)

The wing is elevated or depressed by deformation of the tergum



Anatomy of the Tergum

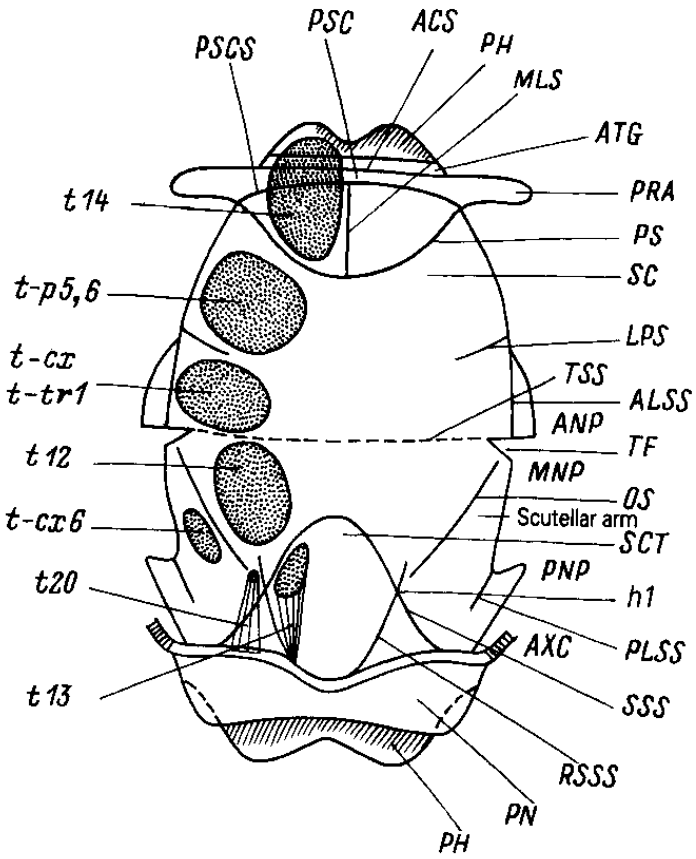
Tergum parts are separated by internal skeletal folding, ridges, and sutures.

Tergum composed of notum, and postnotum.

The notum can be further subdivided into the prescutum, scutum, and scutellum (PSC, SC, SCT)

During flight each part of tergum reacts to the contraction of muscles by moving in a specific direction or distorting in a particular way.

These complex elastic deformations cause wing movement



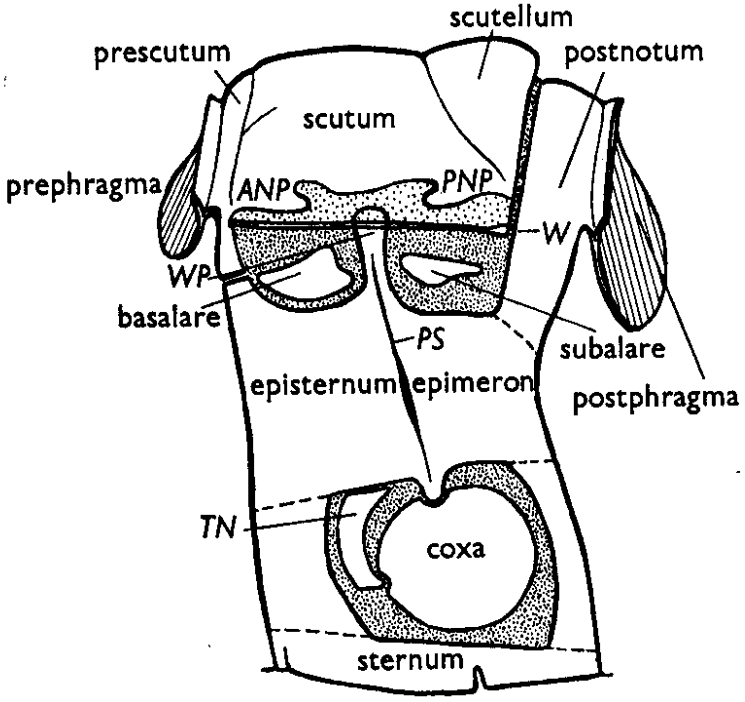
Wing, Tergum, and Pleura

The anterior and posterior phragma (front and rear of the tergum) are attachment points for the dorsolongitudinal muscles

The wing joins the tergum at anterior and posterior attachment points - anterior (ANP) and posterior nodal processes (PNP)

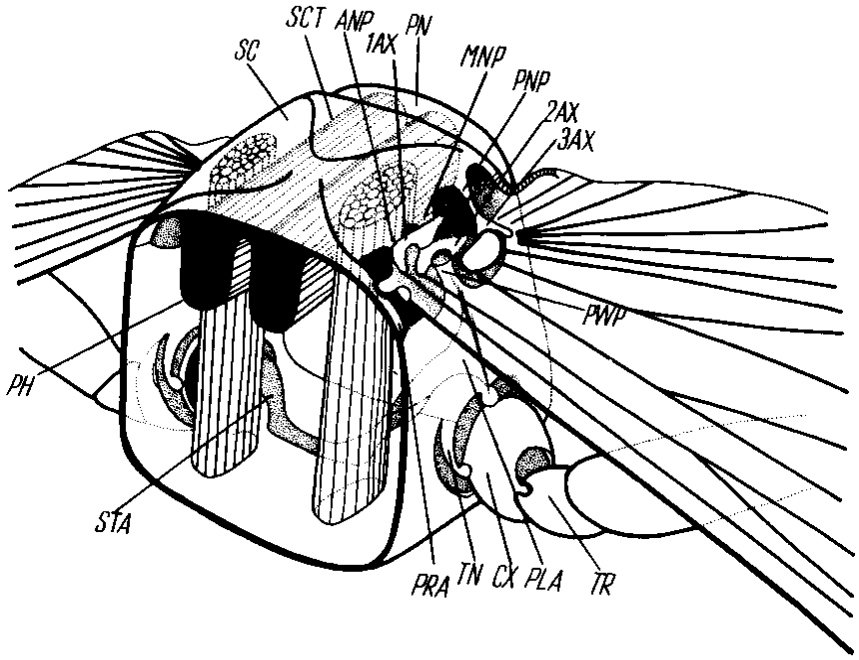
Dorsal surface of the wing connects to the tergum

Ventral surface attaches to the pleural wall



Lateral View of the Pterothorax

Flight Muscles



The Indirect Flight Muscles in Pterothorax

10% to 30% of the total body mass

Two types: indirect and direct.

The indirect muscles
- do not directly effect wing
- attach to the tergum
- distort the thoracic box when contracted
- distortion transmits forces to the wing.
- two bundles of indirect muscles:
  dorsolongitudinal (DLM)
  dorsoventral (DVM)
- dorsolongitudinal span the length of the tergum
- dorsoventral extend from the tergum to the sternum

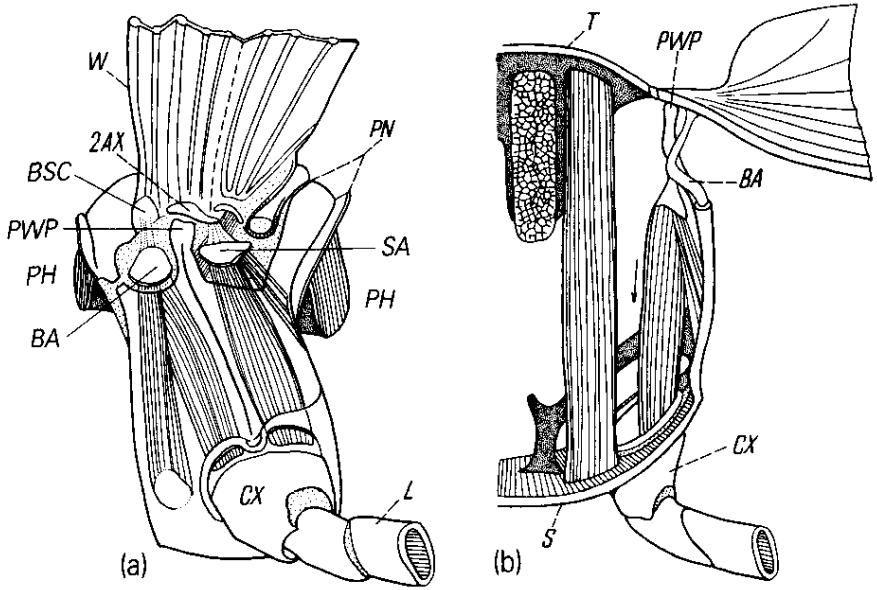
Direct Muscles and Ligaments

The direct muscles connect directly from the pleuron (thoracic wall) to individual sclerites located at the base of the wing.

The subalar and basalar muscles have ligament attachments to the subalar and basalar sclerites,

Resilin - a highly elastic material
- forms the ligaments connecting flight muscles to wing apparatus
- 100 times greater energy storage capabilities than muscle

There are other muscles that are directly inserted into the first and third axillary sclerite.



The Direct Flight Mucles Within the Wing-Bearing Segment: (a) lateral view; (b) cross-sectional view.

More Evolved Insects

Diptera (flies) and Hymenoptera (wasps)

- the indirect muscles occupy the greatest volume of the pterothorax and function as the primary source of power for the wingstroke.
- contraction of the dorsolongitudinal muscles causes severe arching of the notum which depresses the wing
- contraction of the dorsoventral muscles causes opposite motion of notum.
- direct muscles are important in controlling the wingbeat

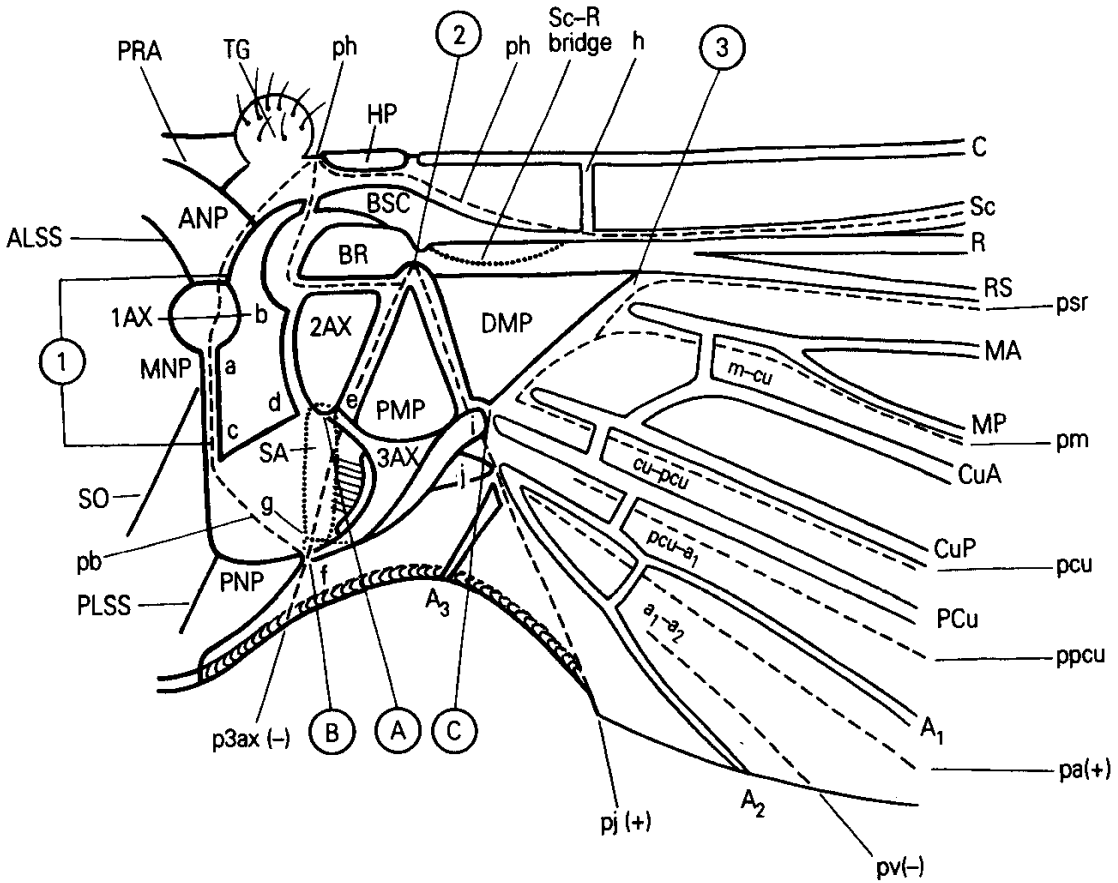
Primitive Insects

Orthoptera (locusts), Coleoptera (beetles), and Odonata (dragonflies)

- direct muscles are responsible for developing the needed power for the up and down strokes

Axillary Apparatus

Region at the base of the wing containing all the intricate mechanical components



Most Important Parts:

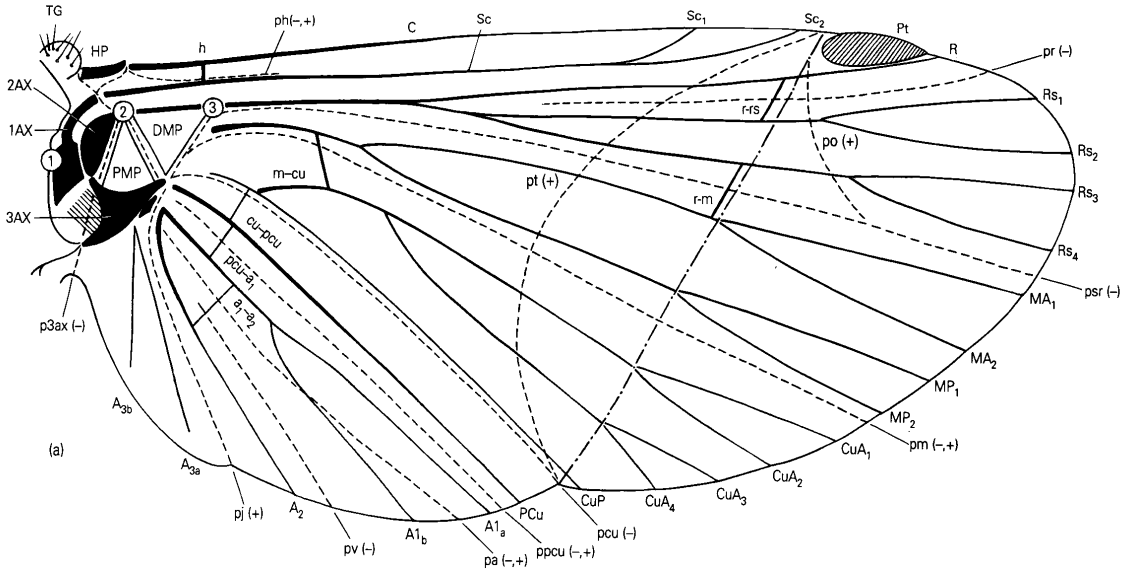
First axillary sclerite (1AX)
- articulates with the anterior notal process
- forms the horizontal hinge

Second axillary sclerite (2AX)
- articulates with an extension of the thoracic wall, the pleural wing process (PWP),
- support the radial vein, (main mechanical axis for the wing)

Third axillary sclerite (3AX)
- important in wing flexing
- vertical hinge.

The Wing

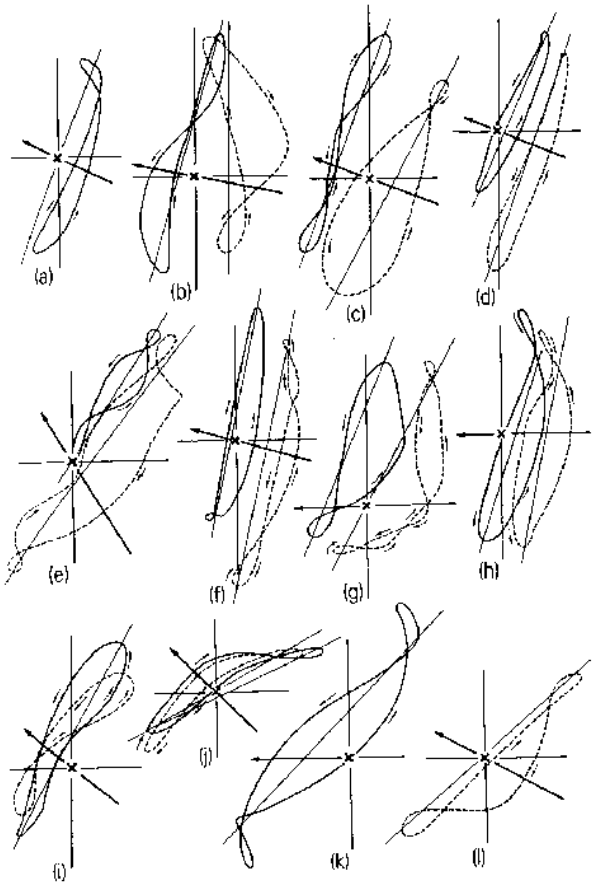
- Membranous cuticle stretched between veins in the wing
- Unlike an aircraft wing, it is neither streamlined nor smooth.
- Folds facilitate deformation during flight
- Veins increase the mechanical rigidity of the wing (alternate in concave and convex patterns).
- Radial vein is the longitudinal rotational axis of the wing, about which occur pronation and supination.



General Wing Layout

Wing Motion

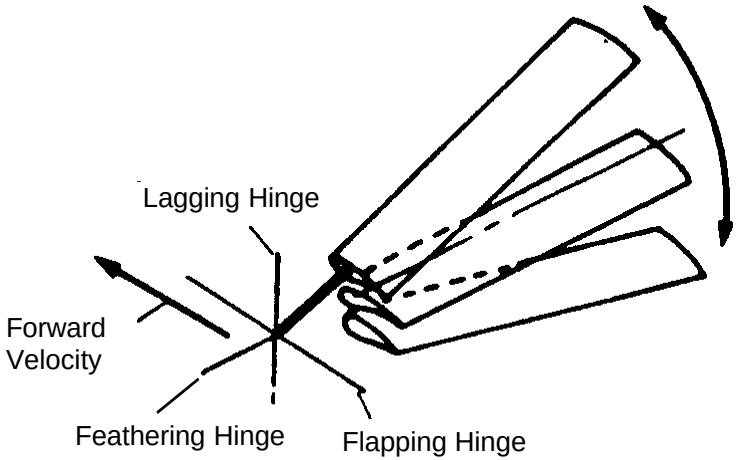
Not simply up and down - much more complex!



Wingtip Trajectories

Wing Motion

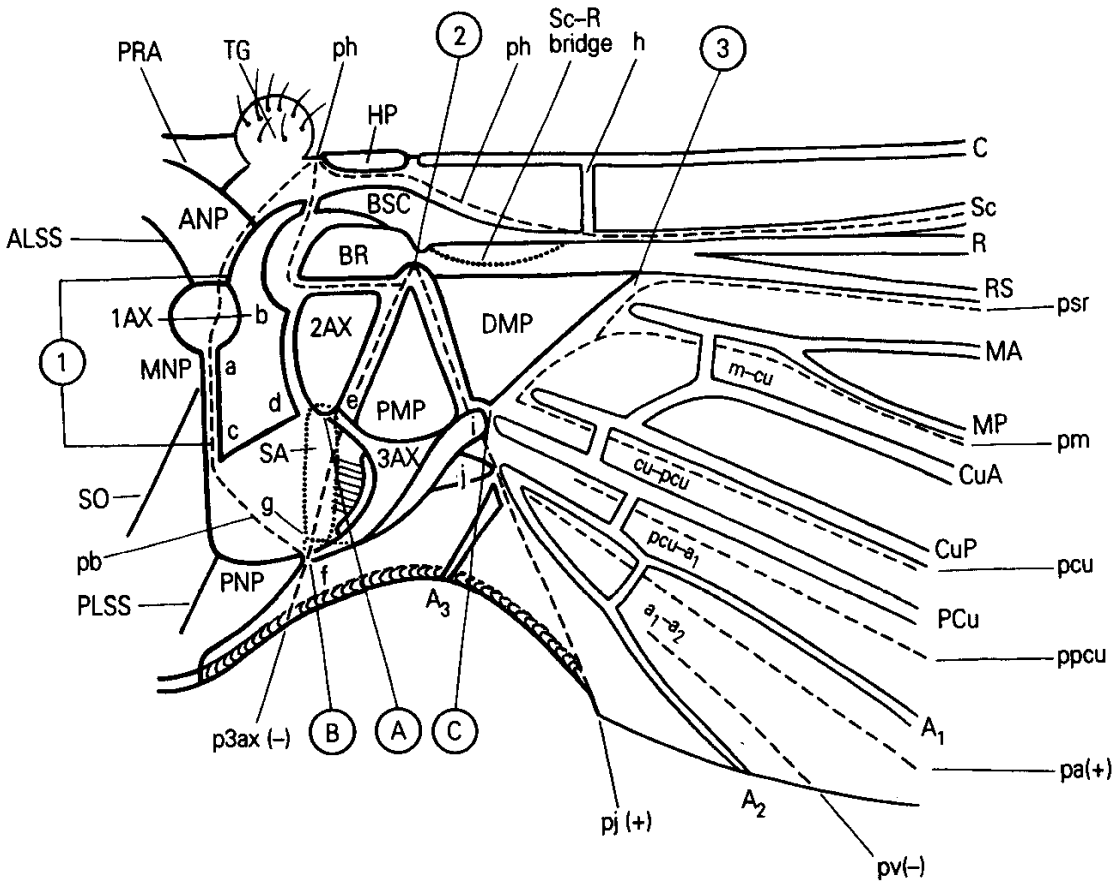
Can consider as motion as being composed of three different rotations:
flapping, lagging, and feathering



<u>Three Hinges of the Wing Apparatus</u>
Horizontal (flapping)
Vertical (lagging)
Torsional (feathering)

Each hinge occurs at the intersection of a vein and a fold

Hinges



The horizontal hinge ①

- occurs near the base of the wing next to the first axillary sclerite
- this hinge allow the wing to flap up and down.

The vertical hinge ②

- located at the base of the radial vein near the second axillary sclerite (2AX)
- responsible for the lagging motions of wing,

The torsional hinge ③

- more complicated interaction of sclerite and deformable folds

Four Phases of Wing Motion

1. depression and turning forward
2. turning backward and beginning supination
3. elevation and end of supination
4. pronation

Flight Variables

- wingbeat frequency: the frequency of oscillation of the wing during a stroke

- stroke angle: the full angular displacement of the wing during a complete stroke

- stroke plane angle: the angle between the stroke plane and the vertical axis

- body angle: the angle the between the longitudinal body axis and the flight path

Bi-Motor Type Flight

Dragonflies (Odonata)

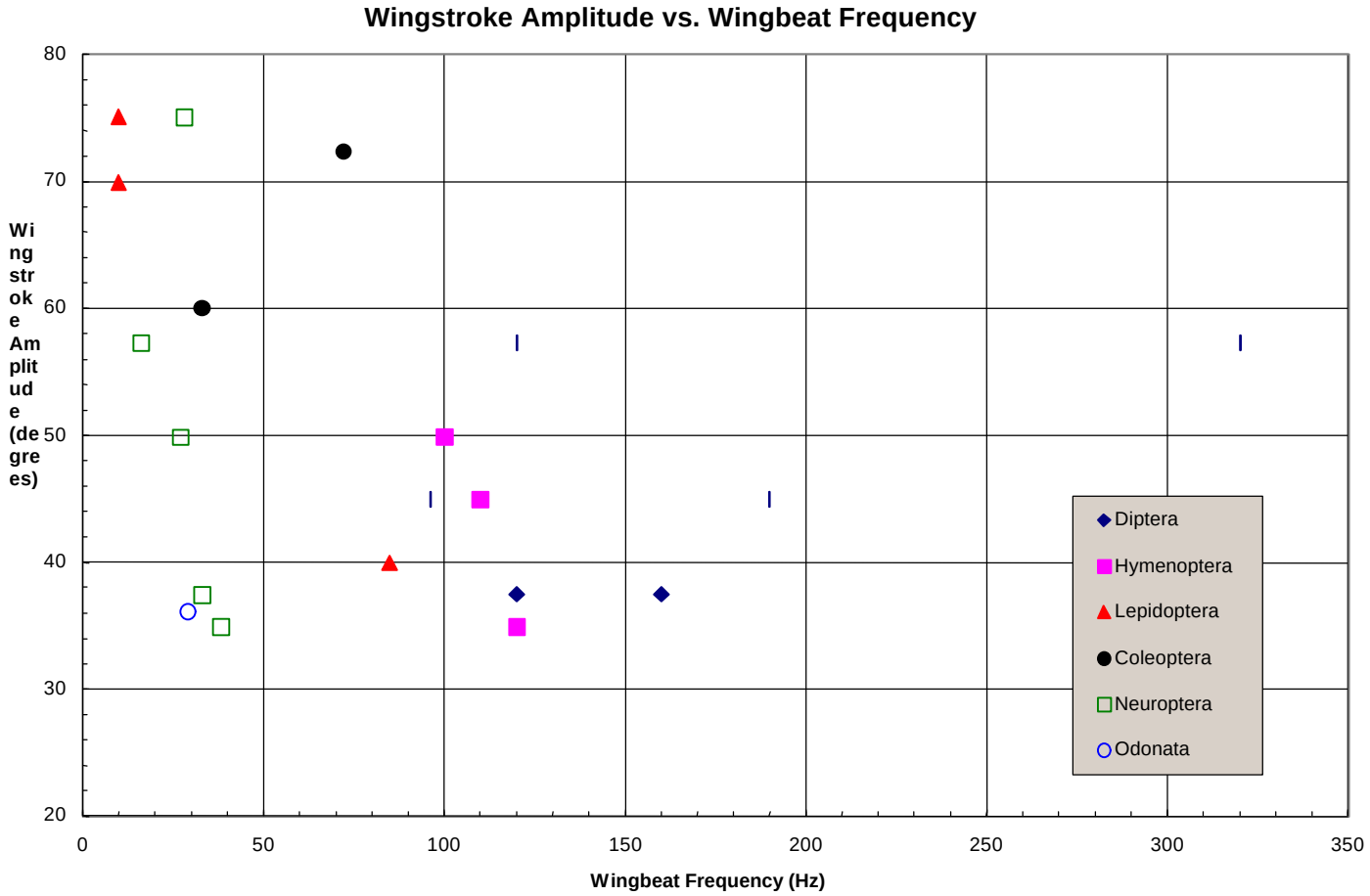
- extreme functionality of the two wing pairs (two motors)
- complete independence of each of the four wings
- high maneuverability
- gliding and high-speed flight
- low wingbeat frequency (25-30 Hz)
- low stroke amplitude (~ 30°)

High-Frequency Type Flight

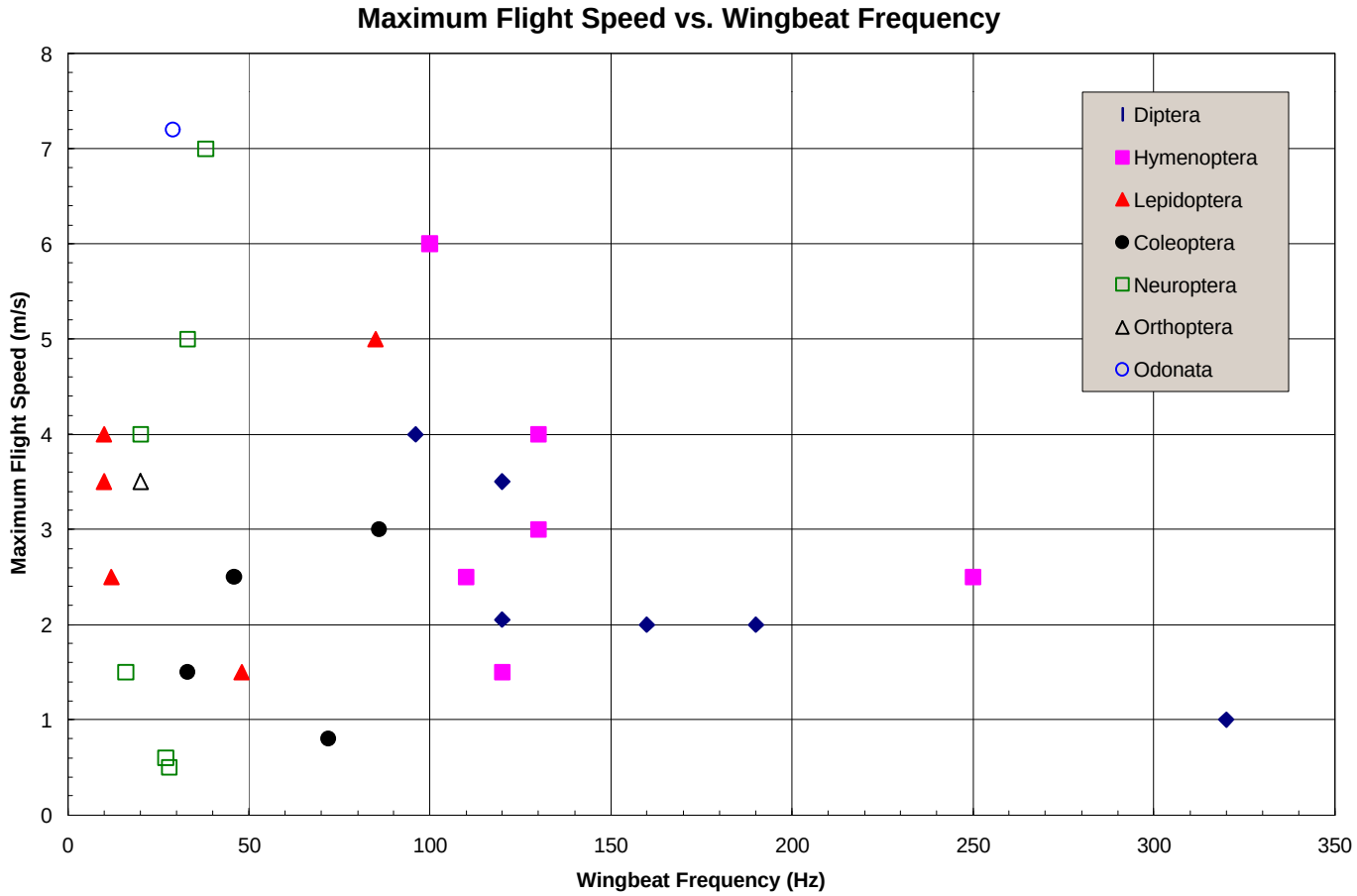
Hymenoptera (bees and wasps) and Diptera (flies and mosquitoes)

- high wingbeat frequency (>100 Hz),
- low -medium stroke amplitude
- high speed flight
- enhanced maneuverability
- variable stroke plane angle - hover

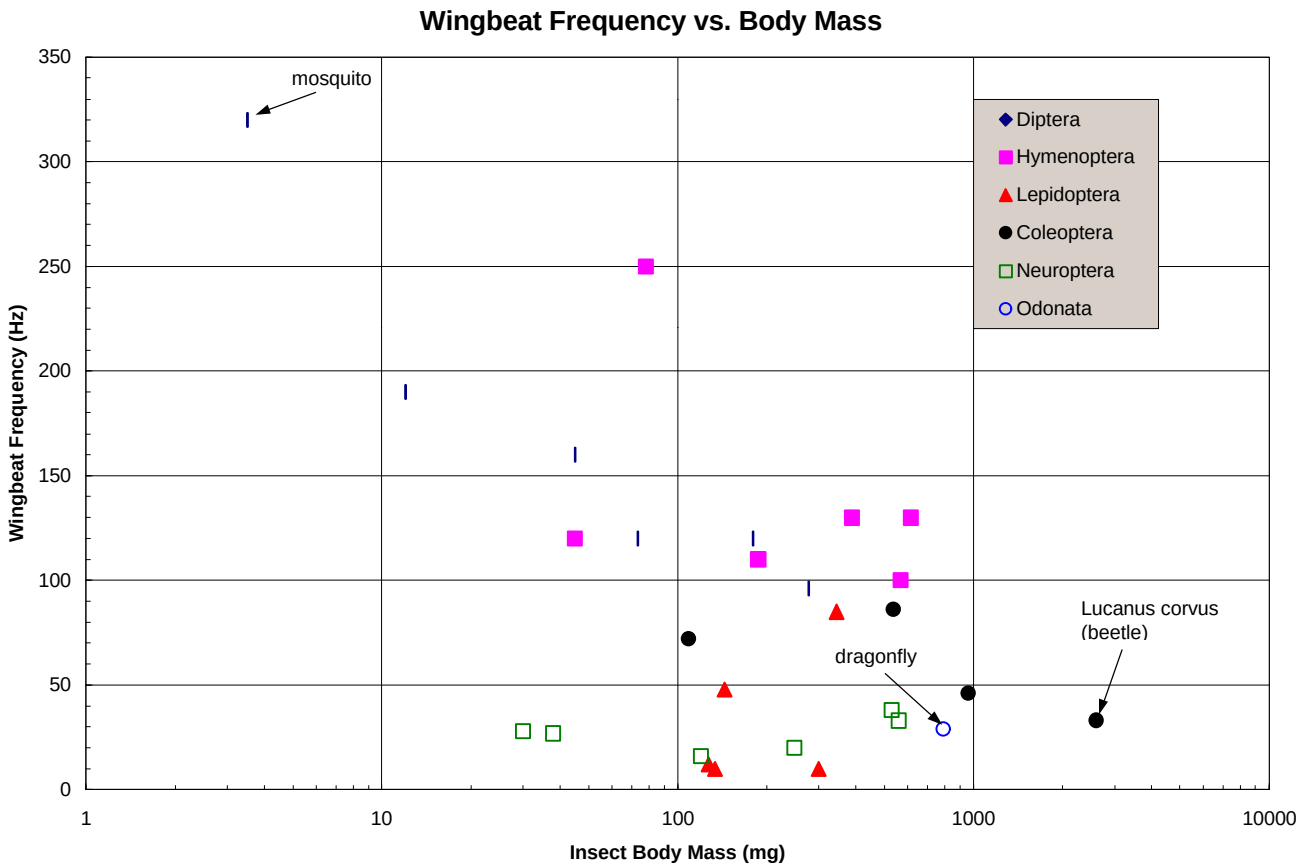
Wingstroke Amplitude vs. Wingbeat Frequency



Maximum Flight Speed vs. Wingbeat Frequency



Wingbeat Frequency vs. Body Mass



Wing Loading vs. Wingbeat Frequency