ANALYSIS OF THE STRUCTURE AND MECHANISM OF WING FOLDING AND FLEXION IN XYLOTRUPES GIDEON BEETLE (L. 1767) (COLOPTERA, SCARABAEIDAE)

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Abstract: This study presents the structure and functions of flying wings in beetles (Coloptera). Structural analysis and function of multiplanar flexion and the structure of the wings in selected beetles were also carried out. The author developed a method of determination of points, structures and surfaces on the wing in folding and flexing motions. The paper describes the system of veins, foils and folds in the wing. Photographs of the wing in different phases of folding and flexion are presented in the paper. The paper emphasizes practical applications of the method of analysis in bionic mechanisms.

Key words: Hind Wings, Structure, Mechanism, Folding and Flexion of Wings

1. INTRODUCTION

The aim of the present paper is to analyse the structure of flying wings in beetles which at rest are folded and tucked under the wing case (elytra). Spread wings represent a drive for an insect for moving in aerospace. Research into real systems regarding structural analysis of mechanisms and application of bionic modelling encounters difficulties at the stage of determination of system structures and their performance. The discussed subject area is contained in the field of entomology and bionics.

As a field of knowledge, bionics encompasses research and cognition of the principles for living organisms. This research is often applied in practical mechanical solutions. Observations and investigations of animal morphology, including insects, have been the focus of numerous researchers for a long time and inspire a variety of researcher. Leonardo da Vinci and Pettigrew’s studies (1891, 1908) are the examples of fascination with flying nature, similar to the investigations by other authors, listed in Samko’s publications (2010).

The function and mechanical mapping of insect wings has been extensively researched in the field of bionics. There are studies in the literature that focus on the analysis of the structure and wing folding patterns in beetles and other insects. Studies by Bhayu et al., (2010) and Nguyen et al., (2010) are the examples of application of wing design in bionics. In these publications, the shape of beetle wings was used to build a macro model of a flying object which simulates wing movements.

The study (Muhammad et al., 2010) analysed folding and spreading of wings and the structure of an artificial wing in a beetle made of metals with shape memory. Wings in this study were based on a simplified model of bending joint with a system of one-point hinges, without considering folding of wing foil in hind folds. In the study (Jin et al., 2010), the method of finite elements was employed for simplified modelling and examination of beetle wing flexion.

Application of modern composite materials in construction of flying models of wings in bats, butterflies, crickets, dragonflies and beetles was presented in the study by Pornsin-sirirak et al., (2001). Closing functions of the first pair of wings were discussed in a study by Frantsevich (2012).

The use of wings is a form of adaptation of beetles and other insects to their environment. It is connected with evolution and further specialization to prevent from extinction through searching for food and colonization of new terrains. The wings can be hidden under the first pair wings (elytra). The hiding motion is composed of the main movements of folding and flexion of wing components. Connection of these movements causes that the wings are completely tucked under the elytra.

Bionic structure of the wing results from very long evolution and it meets the optimal functional demands, without unnecessary additional components.

In order to examine the wing in the beetle analysed in this study, the analysis focused on hind wings of Xylotrupes gideon beetle that belongs to Coloptera family, which is characterized by high activity in flight.

Microscopic examinations provided the basis for the development of the methodology of structural analysis and for dimensioning of the analysed wing. The structural analysis involved determination of points, regions and planes in flexion joint and folding the components of the internal structure of the wing.

2. MORPHOLOGY AND FUNCTIONS OF FLYING BEETLE WINGS

Presence of wings and ability to fly are most unique properties of insects. Flight of beetles is possible due to complex movement of mostly hind wings around an axis close to the long axis of the body and axis of the wing.

Complex movement consists of ascendant and drive movement. Wing movement in different planes is possible due to a mechanically complicated mechanism. The wing motion is generated by the work of trunk muscles and elastic deformation of the thorax by means of thoracic and abdominal muscles, de-
scribed in the studies by Szwanwicz (1956) and Hass (2001). The study by Dudley (2002) contains a description of the flight evolution and biomechanics, structure of wings in different insects and their kinematic and aerodynamic properties.

A wing, as a bulging part of a body, is attached flexibly by means of an articular membrane. The main elements of the wing described in the studies by Szwanwicz (1956) and Pławilszczykow (1968) are foils, veins, nerves and hemolymph. The hemolymph circulates in veins which are formed in the locations of the nerves and tracheae. It is a mixture of water, organic and inorganic matter. The hemolymph contains the suspension of blood cells, haemocytes and other components, such as proteins, amino acids and cations (sodium, potassium, calcium and magnesium) or anions.

The main component in morphology of skeletal parts of insect’s body and wings is chitin. Chitin is numbered among polysaccharides from the group of natural polymers. They include e.g. collagens, casein, wool, natural silk, spider’s web, cellulose and its derivatives, starch, gum Arabic, lignin and natural rubber. Natural polymers are produced by living organisms as structural components of tissues. Chitin is a material that reinforces insects’ skeletons. It is white, hard and little elastic substance. Chitin exhibits hydrophobic properties, high strength and is poorly soluble in water and the most of the solvents. Chitosan, obtained synthetically, is a derivative of chitin. These biopolymers can form different morphological structures used in medicine.

Veins are chitinized pipes and provide a scaffold for the wings. They cover an insignificant part of the wing, but are a basic component to support the stiff, double-layer wing membrane. The spaces between the veins are termed cells or segments.

The photograph below (Fig. 1) presents a male beetle Xylotrupes gideon (Linnaeus, 1767) belonging to the family Scarabaeidae and subfamily Dynastinae.

**Fig. 1. Xylotrupes gideon (L.)**

The main surface area of the wing is taken by a flexible and strong layered system of two foils that form a membrane with veins. Connections of the veins and foils allow for great lifting surface at minimum weight.

Mass of hind wings of different beetles described in a study by Geisler (2011) ranges from 1 to 2.5% of body mass of the insects, whereas the elytra mass accounts for 3 to 8% of the total mass.

Movable wings area connected with musculoskeletal system of the insect. They are attached to mesothorax and metathorax by means of wing joints.

In beetles, the first pair of wings (elytra) is typically transformed into sclerotized hard wing case which in the most of species are used to protect the second pair of wings (alae) tucked under the elytra when unused. They have a spatial and complex structure that provides them with great strength. The morphology and composite microstructure of elytra have been presented in the studies by Chen et al., 2007a, 2007b).

When not in flight, these covers protect folded wings, abdomen, mesothorax and metathorax. In flight, the elytra are either raised totally or only lifted a little to enable spreading out the hind wings. These covers are also equipped with a specific system of interlocks to ensure a strong connection with abdomen and thorax when unused.

The main propulsion in beetles is produced by the motion of hind wings. However, the forewings (elytra) have also some effect on generation of propulsive forces, which was demonstrated in the study (Sitorus et al., 2010).
A study by Jaroszewicz (2009) presents the analysis of aerodynamic forces that act on a miniature wing of a flying object, named entomopter.

Hind wings in beetles are usually much longer than the elytra. In order not to be damaged they must be capable of reducing the dimensions and be tucked under the covers. This is enabled by folding them along the body and flexing under the elytra.

The reduction in dimensions is also possible through internal folding the wing’s membrane along folds. Studies by Bethoux (2005) and Wootton (1979) describe the system of veins and folds used for folding wings in insects that belong to different orders.

The chitin of foils and veins is broken in locations of folds. The study by Hass (2000) found the content and presence of resilin in folds on wing membrane in a Pachnoda marginata beetle. Resilin is a protein (polymer) with irregular structure, present in nature in jumping (e.g. flea, Aphaniptera) and flying insects. The insects frequently use its elasticity and capacity to be deformed repeatedly (e.g. flexion) and store energy very efficiently.

Folding a two-part wing is composed of the motion of its main part in the wing joint and folding in the bending joint in the wing’s plane. Flexion might occur once into two parts or twice into three parts.

Wing connection with the insect’s body is supposed to provide it with highest possible frequency of movements while maintaining the relative motion in specific planes. Motion planes result from muscle movements, movements of insects’ abdomen and the elasticity of the wing.

Functionality of the wing largely depends on its activation during motion (flight) and the ability to fold and bend it in order to protect the wing when unused.

The photograph below (Fig. 2) presents an abdomen of a bee and a distinct sulcus (marked as br in the picture) on the abdomen to fit the veins C+Sc+R1 of the right wing.

**Fig. 2. Wing in resting state**

Shape of the wing must meet its aerodynamic demands and allow the wing to change the shape in upward and downward motion both in vertical and horizontal planes. These demands are satisfied by elastic foil in wings and the related changes in shape around the long axis.

Changes in wings’ shape are connected with muscular and articular activity. A wing is maintained outstretched through contraction in the muscular system. When the muscles are relaxed, the wing stops to be tight and moves partially towards the hind part of the body. Further motion of the wing towards the hind side results from the contraction of a muscle in one of axillary plates and its rotation. The work of this muscle plays the main role in folding the wing.

One of the axillary plates locks and determines the motion of a part of the wing (RA). Mutual movement of axillary plates can be viewed as a lever mechanism motion.

Changes in shape and dimensions are necessary to fold the wing and hide it under the covers. The wings might be tucked under the elytra which are totally open or only lifted a little (Cetoniidae). Folding and drawing the wing in is facilitated by the indenta- tion in lateral edge of the covers.

In order to classify and provide taxonomy for beetles, a special nomenclature of veins has been used in the literature. There are longitudinal veins along the wings that include: costal vein, subcostal vein, radial vein, medial vein, cubital vein, axillary vein and jugal vein. All the veins, apart from the first one, might be branched. Besides the longitudinal veins, there are also transversal veins.

Description of venation used in entomology was presented in the studies by Plawliszczikow (1968), Razowski (1987, 1996), Stebnicka (1978) and Szwanwicz (1956). The study by Stank (1974) termed bending joint as radial sector root (RSR).

### 3. FLEXION AND FOLDING OF INTERNAL STRUCTURES OF BEETLE WINGS

In mechanical terms, the wings, folded and bent at rest, are a complex structure. Connection of the wing with the body by means of the wing joint and connection in the bending joint are regarded to be some of the most complicated mechanisms in the insect’s body.

The many-level mechanism of flexion makes a structure of an insect wing very complex and has more components than uniform wings.

The structure of the spread-out and folded wing is not a flat plane. Insect adopt the shape of the wing so that it is the most aerodynamic.

A wing is composed of two (or more) main parts. The base part is attached to the thorax with the wing joint, whereas the second part is connected to the base part in the bending joint. An important function of hiding the hind wing under the elytron results from its arrangement in horizontal plane and is associated with bending the wing.

Movement of the second part of the wing in bending joint might occur in the direction which is consistent with the main direction (rotation) of folding for a single bending. In double folding, the direction of the movement of this part might be opposite or complex for the last bent part of the wing.

Proportions in wing flexion depend on the ratio of wing length to cover length. They vary and depend on the family a beetle belongs to. Folding of the wing membrane occurs in a fan pattern in specific planes, alternately along the folds that are formed in the wing's membrane.

Mutual arrangement of folds in wings has been broadly discussed in studies by Szwanwicz (1956) and Hamilton (1971, 1972). When folding the wing membrane, the jugal part (Ju,
Fig. 6) of the membrane folds along the jugal fold (fj) and is placed under the anal part (Fig. 6) in a complex motion on the abdomen.

The system of wing folding is capable of increasing the lifting surface with the least possible surface (dimensions) of the wing when at rest. Apart from folding alone, the dimensions are also reduced by an accordion-like folding of wing membrane.

Arrangement of the wings under the elytra must take into account the limited space and the bigger wings must be overlapped. The degree of overlapping of the foil in the two wings under the elytra varies depending on the family and was presented for selected families of beetles in a study by Geisler (2011).

The figure below presents a wing of the analysed beetle in the phase of unfolding.

Fig. 3. Right wing in the phase of unfolding

4. STRUCTURAL ANALYSIS OF WINGS

Structural analysis of a wing necessitates the knowledge of connecting the parts into the kinematic pairs, determination of the degrees of freedom and the mobility of mechanisms.

Structural analysis of the wing mechanism involves selecting and determination of the elements of the wing which allow for folding. A beetle wing represents a complex system of the main components such as veins, foil and folds.

The figure below presents a beetle wing with distinct spatial bending joint (Fig. 4).

Fig. 4. Spatial structure of wing flexion

Wings from several initially analysed families of beetles were selected for the examinations. Kinematic pairs and internal nodes were also separated. The criterion for searching for the points was their location at the intersection of the folds where a change in the shape of the wing membrane surface was observed. Deformations of the membrane caused creation of the rigid structures (areas). These structures typically took the shape of triangles, quadrilaterals and complex spatial shapes (Fig. 6).

The figure below presents the right wing of a beetle in flexed state (at rest) (Fig. 5).

Fig. 5. Flexed (resting) position of the right wing

A precondition for adopting the structure as constant (rigid) was invariability of its shape in movement phases when bending and folding the wing membrane. When moving the structures, the folds were formed at the surface of the wing.

The folds between the points formed lines. The folds contain the ridges (g.) and valleys (d.). It was adopted that a ridge moves towards the upper surface of the wing and a valley moves in opposite direction.

The folds were marked with symbols denoting ridges and valley (e.g. g. 1-4, d. 10-11), and, additionally fa, fj,..... (Fig. 6) and the structures (e.g. s. 1-2-3), containing the adopted numbering of points. For essential points located at the lower edge of the wing, the authors adopted the following symbols: b1, b2,... For selected points located in the area of wing joint the adopted symbols were ps1, ps2.

Wing flexion is possible only as a result of changes in position of the planes which contain rigid structures.

Analysis of multiplanar mechanism of wing flexion and folding revealed that arranging and folding the structures with respect to each other might be total or partial.

Selected folds in the wing, such as ridges and valleys maintain their positions with respect to each other that do not form flat surfaces, with planes positioned at different angles. It was assumed that the structures form the U shape.

The structure of a wing also contains V-shaped triangular rigid structures. Folding the structures along the folds might be either total or partial.

Combination of the U-shaped and V-shaped structures naturally stiffens the structure when the wing is unfolded and folded.

The U structure is maintained in e.g.: rigid structure s. 18-26-29-ps4-ps5-14-18 with valley d. 18-ps4, structure s. 1-2-24-14-1 with valley d. 14-24-2-1.
When determining the structure of the wing, the author analysed dislocations (rotation) of the defined points and structures with respect to each other.

The photograph below (Fig. 6) presents the right wing of the analysed beetle with the marked points and structural diagram and symbols for folds, veins (Ŝ) and thickness zones (h).

Fig. 6. A beetle wing: Xylotrupes gideon (L.) with the assumed structural components

The photograph of the wing (Fig. 6) presents the description of veins, structures and areas: R – area of radial veins, (R1, R2, ...), M – area of medial veins, Cu – area of cubital veins, A – area of anal veins, An – anal area of the wing, Ju – jugal part of the wing, Ax – area of axillary veins, C – costal vein, Sc – subcostal, Sb – wing joint, Sg – bending joint.

Figure below presents magnification of the diagram of rigid structures in the bending joint (Fig. 7).

Fig. 7. Magnification of the diagram of points and structures in the bending joint

The following rigid structures and their component movements:
- system C+Sc+R1, (s. 1-14-ps5-ps1) forms a structure with symbol (RA);
- U-structure: s. R3 (4-b1)-4-b1 z d. 4-b1 (zigzag);
- solid: s. 18-26-29-ps4-ps5-14-18, forms a system (vein) with symbol (RM);
- solid: s. b8-ps3-21-23-22-b7;
- structure s. 21-22-23 forms an internal V system with d. 21-22;
- solid: s. 1-b1-b2-4;
- solid: s. 1-4-3, including g. 1-4 folds into the fold d. 4-5, and, simultaneously, s. 1-4-3 bends (rotates) around g. 1-3;
- within the macrostructure of the wing, the section of the ridge g. 5-6 remains vertical after folding;
- solid s. 8-11-10 and s. 10-11-16 are arranged vertically with g. 10-11 perpendicular to the wing surface;
- solid s. 1-11-2, s. 2-11-8, s. 2-8-24, s. 24-2-8 form a complex system which folds in V system along d. 1-2-24-10-16;
- structures: s. 19-b7-20 and 19-20-30 form the V system with g. b7-ps3 and fold totally along f. b7-20-30-ps4 on s. b7-ps3-ps4;
- solid s. 7-9-19-29-26-7 and s. 19-30-29 form the V system with 9-b7-19 and fold under the solid s. 18-26-29-ps4-ps5-14-18 along d. 9-19-ps4;
- the fold g. 9-b5 folds with d. 7-9 (significant);
- solid s. 19-30-29 and s. 19-20-30 fold with respect to each other along d. 19-30;
- split vein (Ŝa) provides a reinforcement for the structure s. b7-b8-ps3-ps4;
- after wing folding, the structure b2-b3-b4-18-5-4-b2 forms one plane in consideration of folding d. 4-5 and g. 5-18 with folds g. 18-7 and d. 7-9.

When marking the points of structures, the author adopted the right hand rule. Moreover, the locations of the selected reinforcing veins were also marked 21, 22, ... . (Fig. 6).

The main fold for folding the wing membrane outside the rigid structures in bending is the fold g. 9-b5.

When folding the hind part of the wing it is essential to fold the jugal part along the fold: d. b10-27-28, in conjunction with folding the anal part around the fold: g. b8-27. The fold f. b11-28
is connected with the insect abdomen (Fig. 6).

Locking the open wing is possible through contraction of a system of muscles that unfold and drive the wing motion.

The motion (opening) of the second part of the wing in bending joint occurs without using muscles because they do not exist in the main wing membrane.

This is possible through changes in the structures that form the U shape. These include the external structures: s. 1-14-ps5-ps2-ps1-1 (RA) and 18-ps4-ps5-14-18 (RM) and the structures between them.

Structures (Ra, RM, Fig. 6) perform a relative (scissors-pattern) motion that is formed by a complex dislocations in the wing joint. It is essential for this motion to maintain the chain marked with points: 1-4-5-18.

When bending and folding the wing, some local structures and folds occur. Their existence is necessary as they allow wing to fold and bend and the surfaces to overlap. One of these fold is: f. b4-9.

The analysis assumed that the veins in the wing are elastically arranged in bending planes, maintaining the global flatness of the wing which is an elastic membrane.

Classical kinematic pairs with one degree of freedom (rotating pair) are present in bending joint in certain places (e.g. 1, Fig. 6) and in wing joint. Descriptions of kinematic pairs have been presented in example studies by Artobolewski (1988) and Miller (1996).

In the system of C+Sc+R1 (RA) (Fig. 6), vein R1 has special 'ribs' perpendicular to the wing surface. It contains elastic structure in the area of bending joint and allows for rotation of the R2 vein, only in the wing plane.

A substantial majority of the wing planes when at rest are parallel to each other. Hence, the flatness of the wing can be assumed for the resting state.

The obtained form of the wing corresponds to the requirements of minimal dimensions in the plane which is parallel to the flat surface of folding and bending. Interfolding of ridges and internal folding of folds is an element that stabilized the wing.

The components of the wing adopt a spatial structure within certain borders (dimensions of the macrostructure determined by the thickness of the wing).

Basic parameters of the beetle and its wings analyzed in the study included: total length of the beetle (70 mm), wingspan (135 mm) and parameters of a single wing: mass (~0.09 g), length (60 mm), width (23 mm), section 10 mm (Fig. 1).

The dimensions of the folded wing are presented in the photograph (Fig. 5) against the background of a graph paper. The smallest distances between the points and the internal structures have dimensions of 0.5-1.5 [mm].

The thickness of the components of the wing was also determined. It accounted respectively for the areas: h1-0.35, h2-0.34, h3-0.20, h4-0.13, h5-0.07, h6-0.025, h7-0.09, h8-0.015 [mm] (Fig. 6). The thickness of the structure of the wing in the binding joint ranged from 0.6 to 1.6 [mm].

Tucking the wings under the elytra is a combined effect of several factors. It was observed during the study that arrangement of wings under the wing case is facilitated by the indentation in the beginning and at the end of the elytra that perfectly fit the natural curvature of wing and bending joints. Stabilization of the folded wings and abdomen is ensured by a sulcus profile (br) where the MA structure is arranged (Fig. 2, 3).

It was also observed that when the folded wing is arranged, the final arrangement of the wing on the abdomen occurs as a result of pressing it with the wing case. This mainly concerns the structure s. 18-26-29-ps4-ps5-14-18. Closing the wing case causes the deeper interfolding of the rigid structures and final arrangement of the wing.

Furthermore, wing folding is supported by interrelated 'sliding' motions of the segments of abdomen and a possible additional motion of hind legs in selected families of beetles.

An essential factor for the function of wing flexion is the constitution and stiffness of the vein Cu/b7-ps3, and cutting it weakens the mechanism of opening of the second part of the wing.

The microscopic examinations were carried out by means of a technical stereoscopic microscope PZO Warszawa with magnification of 4/100x with special sectional diode light source. Photographs and films were recorded by Nikon D90 (12.3 MPx) with macro lens and equipment.

5. ANALYSIS OF LOCAL DEGREES OF FREEDOM IN THE STRUCTURES

Beetle wings have varied structure and constitution. In order to determine this differentiation, a method of calculation of local mobility in internal structures was employed.

An example structure with a determined degree of local mobility in internal structures is presented below. The simplified method of calculation takes into consideration the presence of kinematic pairs of I class defined in fundamental studies on the theory of machines and mechanisms by Artobolewski (1988) and Miller (1996).

The calculations assumed mutual spatial displacement of the structures reduced to one plane. The mobility formula was: R=3n-2p1, where: n - number of movable parts, p1 - rotary connections along the lines between the structures.

The following pairs were determined in the system of structures presented in Fig. 8: 1-2, 1-3, 2-4, 3-5, 4-6, 5-6, 5-7, 6-8, 7-8. The calculated mobility amounts to R=3

![Fig. 8. System of internal folding of the structures](image-url)
In order to use the above method, it is necessary to conduct the analysis of the component lengths of the structures. The relations between the lengths of the sides in the analysed structures determine the internal angle of folding and the adopted position of the plane with the structure in the wing space.

Local degrees of mobility necessitate consideration for the principles of formation of folds on flat surfaces with respect to each other, similar to paper surfaces used in Japanese origami.

The method of determination of local mobility is used for evaluation of the level of complexity in wings and will be used for further research. It can help introduction of necessary simplifications in the structure of modelled wings.

6. CONCLUSIONS

The biological and mechanical structure of a wing is very complex. Analysis of the structure of the wing in different beetles points to a variety of structures, morphologies and wing folding and flexion patterns in this family of insects.

This study presented the analysis of selected mechanisms of flexing the wing in its articulation (wing joint) and internal folding of the wing structures. Some simplifications can be employed in wing design, which result from the properties of modern materials while maintaining their functions. The structure of the beetle wing presented in this study meets the requirement of continuity of wing surface throughout all the motion phases.

It was demonstrated that the motion of the second part of the wing in bending joint is affected by several factors, of which the most important is the change in position of specific U-shaped structures with variable parameters. It is essential that the most components in wing structure, including a part of vein systems connected with the structures discussed in this study fits the described U and V shapes. There are some common elements of the wing structure in beetles and other insects which can be used for further analyses and designs.

Further research should focus on the analysis of all the wing motions, including the motion of axillary plates in the wing joint, regarded to be a complex lever mechanism motion as well as flat and spatial mechanisms of different classes.

There are a number of patterns for folding and bending of insect wings. It is necessary to analyse greater number of structures of beetles from the collections owned by the author. Other structures of wings exhibit different number of points typical of different families, types and species of beetles from the collections owned by the author.

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