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ANALYSIS OF THE WING MECHANISM MOVEMENT PARAMETERS OF SELECTED BEETLE SPECIES (COLEOPTERA)

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This study presents a structural and functional analysis of the wing bending and folding mechanism of a selected beetle species. Insect motility studies, with regard to the anatomical structure, were performed. The main inner wing structures were highlighted and their mechanical properties and functions were determined. The structure parameters as mechanisms bodies that allow wings of various beetle species to bend and fold were defined.

Key words: bionic, wing, movement parameters, folding.

1. Introduction

The research of the mechanical properties and the mechanisms structures of insects wing, including beetles, facilitate an understanding of nature solutions. Observation of insects may provide inspiration to design various machines, including micro air vehicles (MAV).

The aim of this paper is to determine the parameters and define the structures of inner wing mechanisms of various beetle species (*Coleoptera*). The obtained parameters and kinematic dependencies will support the development of the MAV's bionic wing model.

The research into real systems, regarding the structural analysis of mechanisms and the application of bionic modeling, encounters difficulties at the stage of determination of system structures and their performance. The article (Haas, 2006) presents the construction of the wings of winged insects (*Pterygota*), including the wing-bending joint.

The wing movement is carried out by thoracic muscles and elastic deformation of the body, by means of a thoracic and abdominal muscles described in the work (Szwanwicz, 1956) and (Haas, 2001).

The functionality and the mechanical reproduction of insect wings have been recently 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 that simulates wing movements.

The studies (Muhammad *et al.*, 2010; Mallesh, 2012) contain the folding and spreading of the wings analysis and the structure of an artificial beetle wing made of metals with shape memory. Wings in this study were based on a simplified model of the bending joint with a system of one-point hinges, without considering folding of the wing membrane in hind folds. While in the study (Jin *et al.*, 2010), the method of finite elements was employed for simplified modeling and examination of beetle wing flexion.

The paper (Ha *et al.*, 2013) describes the biomechanical properties of a selected beetle wing using

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MES. Indirect closing and the double rotation of the wing covers of the first pair of beetle wings were discussed in Frantsevich (2011; 2012).

A number of works concerns the construction of flying insect models. In the work (Fenelon, 2010) the construction of the powertrain mechanism for micro flying insects was shown, and in the work (Nguyen *et al*., 2010) angle and force measurements for a simple model of the powertrain mechanism were performed. The main propulsion in beetles is related to the hind wings movement. However, the front wings (covers) are also involved in the production of lift force, as shown in the work (Sitorus *et al*., 2010).

In Poland, the studies of the kinematics and aerodynamic load of insect wings are underway (Czekałowski, 2009; 2012). In the paper (Jaroszewicz, 2009) the analysis of aerodynamic forces acting on a miniature wing of a flying object (entomopter) was presented.

The wing structure results from very long evolution and meets the optimal functional demands. In order to study the structure of the selected insects wings, the hind wings were analyzed. Hind wings in beetles are usually much longer than the covers (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 bending and folding them along the body under the elytra. The dimensions reduction is also possible through internal folding the wing's membrane along folds. The studies (Bethoux, 2005) and (Wootton, 1979) describe the venation and wing membrane fold system in various insect orders.

The beetle wings behavior observation is the subject of many papers. In the study (Hass, 2001), the behavior of the *Pachnoda marginata* KOLBE, 1906 beetle wing during the folding and flapping was analyzed. In the paper (Muhammad, 2010) the *Allomyrna dichotomia* (L., 1771) beetle wing movement was described. This study contains the preliminary analysis of the structure and the wing construction. Also, the wing model design was proposed, however without imitating the exact geometry and stiffness of an insect wing. The biomechanical properties, including asymmetry in wing stiffness resulting from the venation system and veins deployment are important in the wing construction.

In the study (Geisler, 2011) an analysis of *Xylotrupes gideon* (L., 1767) beetle wing was performed, and a methodology for the basic wing inner structure analysis and description was proposed. The structural analysis concerned the determination of points, structures and surfaces on the wing bending joint and the inner wing elements folding. The internal wing structures were isolated and their kinematics functions were defined. In the paper (Geisler, 2014) functions of wings and their behavior during flight were observed. The observations of the wing folding and stacking under the elytra and the position of the antennae and legs during the take-off and flight of an insect were made.

2. Investigated beetle species

The investigated beetle species belong to the order of *Coleoptera*, the *Scarabaeidae* family, and the *Cetoniinae* (species, 1-5) or the *Melolonthinae* (specie, 6) subfamily. Others belong to the *Cerambycidae* (species, 7-9), the *Geotrupidae* (specie, 10) and the *Chrysomelidae*, (specie, 11) family. The beetle species, whose wing mechanisms were analyzed, are listed below:

1. *Chelorrhina polyphemus confluens* (KRAATZ, 1890),
2. *Mecynorrhina torquata immaculicollis* (FABRICIUS, 1775),
3. *Eudicella trilineata* (QUDENFELD, 1880),
4. *Cetonia aurata aurata* (LINNAEUS, 1758),
5. *Trichius fasciatus* (LINNAEUS, 1761),
6. *Melolontha melolontha* (LINNAEUS, 1758),
7. *Aromia moschata* (LINNAEUS, 1758),
8. *Monochamus sartor* FABRICIUS, 1787,
9. *Prionus coriarius* (LINNAEUS, 1758),
10. *Geotrupes stercorarius* (LINNAEUS, 1758),
11. *Chrysomela populi* (LINNAEUS, 1758).

The selected species of beetles reached a body length of *12÷50* [*mm*], wingspan of *30÷125* [*mm*] and weight from *0.1* to *6.5* [*g*]. They were collected from their natural environment (Poland) or came from the author's breeding of exotic species (species 1-3).

Beetles belonging to the *Cetoniidae* subfamily (species 1-4) extend and open their wings by lifting the elytra only a little. Other beetles belong to the families that open their wings only while the covers are raised totally.

Observations were carried out using stereoscopic microscope with the magnification of *x4÷100* (*x2.4-60*), microscopic camera (*5 MPx*) and cameras (*12÷16 MPx*) with macro accessories that enable recording movies up to 30÷1000 fps. The stacking technique was used for increasing the focus depth of the microscopic photographs.

Some of the images used in this paper were made using the scanning electron microscope (JEOL JSM-6610LV, *x5 ÷ 300000*) at the magnification range between *x23÷200*.

3. Functional analysis of folding and bending of beetle wings

The use of wings is a form of adaptation of beetles and other insects to their environment and connected with evolution and further specialization to prevent from extinction through searching for food and colonization of new terrains.

In addition to the flight functionality, the wings can be hidden under the first wing pair (covers). The hiding motion is composed of the main movements of folding and bending of wing components. Combination of these movements causes the wings to be tucked under the elytra.

The beetle wings, folded and bent at rest, are mechanically complex structures. The 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 wing drive mechanism based on the musculoskeletal segment of the insect's body is a comparatively complex structure.

The analyzed wings are composed of two main parts. The base part is linked to the thorax in the wing joint. The second part is mainly connected to the base part in the bending joint. The movement of the second wing part in the bending joint is rotational and is carried out in accordance to the direction of the wing folding and unfolding of the analyzed beetles (species 1-10).

The connection of the wing with the body by means of the wing joint is to provide the possibility of wing movement and to enable some of other functional features. The wing joint is a complex system of tergal plates and groups of axillary plates. Mutual movement of axillary plates introduces limitations to the wing movement only for specific planes and angles. Also, the muscle and abdominal movements limit displacements, planes, angles of wing movement and its internal structures.

The proportion of wing bending depends on the ratio of the wing length to the covers length of selected beetle species. It is diversified within the beetle families. Wing membrane folding is fan pattern in specific planes, alternately along the folds that are formed in the wing's membrane.

The primary wing veins and their branches form the main supporting structure of the wing membrane. It includes the unbranched costal vein (costa - C) and the branched subcostal vein (subcosta - Sc). Both of these veins form the wing leading edge. The subcostal vein is connected to the costal vein by short humeral cross-vein (humeralis – hp) (Fig.1). The humeral plate (hp) has fork-shaped outgrowths (Figs 10, 11).

The connection of the costal and subcostal veins (hp) is further connected to the body by the tegula sclerite, which is overlapping the base of the wing. The wing venation consists also of following longitudinal veins: radial vein (radius, R), medial vein (media, M), cubital (cubitus, Cu), anal vein (A) and jugal vein (Ju). Next to the longitudinal veins there are also cross veins described in the papers (Pławilszczikow, 1968), (Szwanwicz, 1956), (Razowski, 1987; 1996).

In the study (Geisler *et al.*, 2014) three primary wing structures were isolated. These structures allow the wing folding and locking it in the maximum deflection of the leading edge angle. Mutual folds composition are shown in the papers of (Szwanwicz, 1956) and (Hamilton, 1971; 1972).

The wing spread observed in the recorded movies confirmed that the effect of wing bending spread in the wing joint is among other things the result of changes in the insect's vein blood pressure and the structure elasticity described in the works (Dudley, 1999) and (Sun *et al*., 2014).

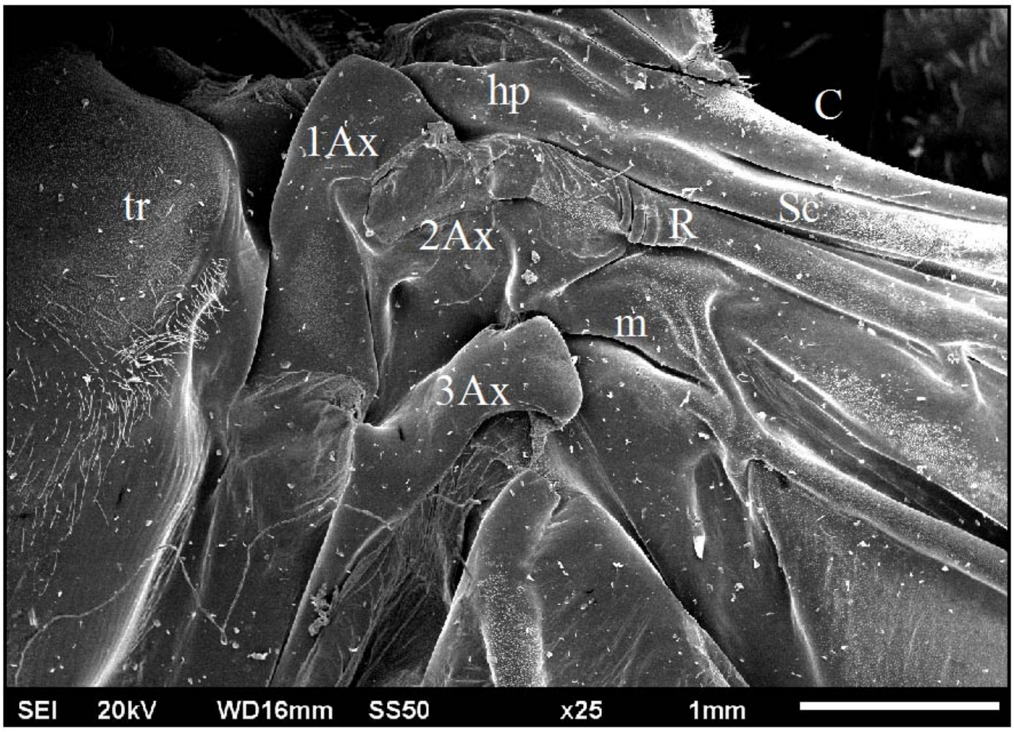


Fig.1. Wing joint of *Monochamus sartor* F., JEOL JSM-6610LV, x25.

4. Structural analysis of beetle wing mechanisms

A beetle wing represents a complex system of veins, membranes and internal structures. It is possible to extract a number of internal structures responsible for all wing functions. During the wing movements, the structures position changes are mutually dependent. The wing unfolding and tucking on the insect's abdomen is a complex movement of the internal structures. A beetle wing may be considered as a system of interconnected components and the insect's body as the fixed body (base).

It was assumed that the isolated groups of structures form the main groups of kinematically linked mechanisms. The first mechanism is the complex folding joint, and the second is the bending joint mechanism. The folding joint is bigger than the bending joint.

Some species of beetles have an auxiliary bending joint. The result of its occurrence is double wing bending. This paper shows this kind of structure based on the beetle, *Chrysomela populi* (L., 1758). In future it is planned to introduce an expanded analysis of wing structures mechanisms of the observed group of beetles.

The third mechanism is responsible for the motility (drive) of the wing and is connected both to the folding joint and insect's body. Movement transmission to the wing is due to the basalar and subalar muscles as well as to the tergite movement (tr, Fig.1).

Reciprocal movement of the internal mechanisms allows performing all of the wing functions in flight and during the wing closing movement. The outward and inward wing movement forces the relative movement of all internal wing body mechanisms. These mechanisms are mechanically connected with the wing drive mechanism.

A structural analysis of the mechanism concerns the designation of wing structures that allow complete submission of the wing, including bending. This requires knowledge of the type of internal structures connections, treated as mechanism body. The analysis requires the designation of movement type of kinematic pairs and their class. An analysis of wing joint mechanism concerns the determination of the boundaries and movement of the axillary plates combined with the wing veins and insect's abdomen.

It was necessary to set the distribution of internal structures and points that define their boundaries as well as types of folds between them and the rest of the wings.

Structures that tend to arrange themselves relatively during the movement of a wing part form flexagonal structures. These structures are mainly composed of triangular facets. The facets are arranged relative to each other partially or completely (submission) along connecting folds (lines).

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. The folds between the points formed lines. The folds contain the ridges and valleys. It was adopted that a ridge moves (solid line) towards the upper surface of the wing and a valley moves (broken line) in the opposite direction. Structure spacialization should meet the compatibility condition for angles and lenghts of the edges of individual facets.

The figures below present the (right) wings and the adopted structures for the selected beetle species.

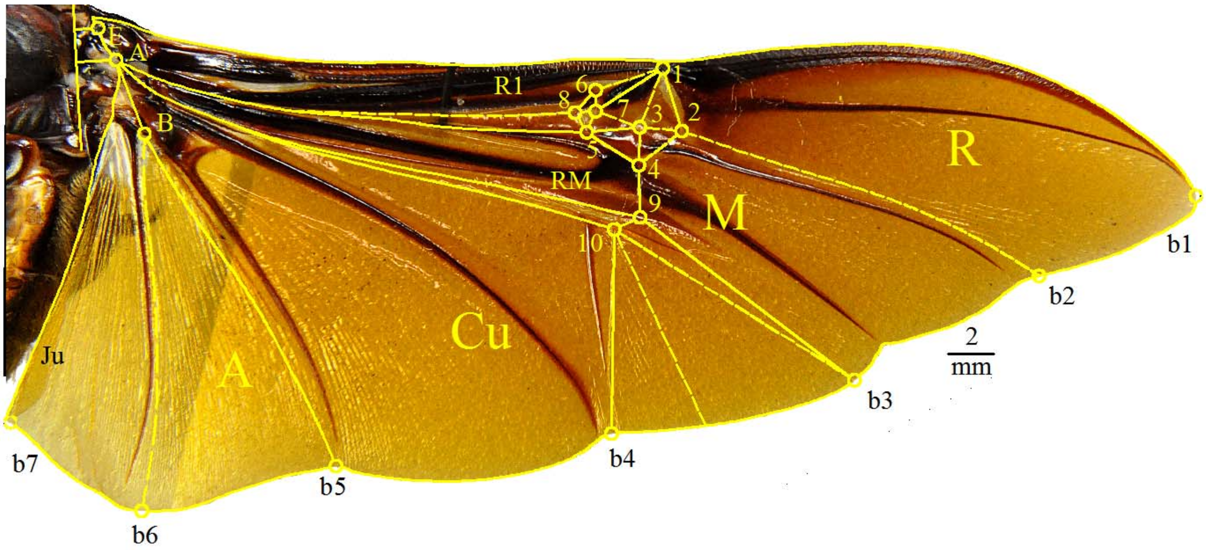


Fig.2. Wing and beetle scheme *Chelorrhina polyphemus* (KRAATZ).

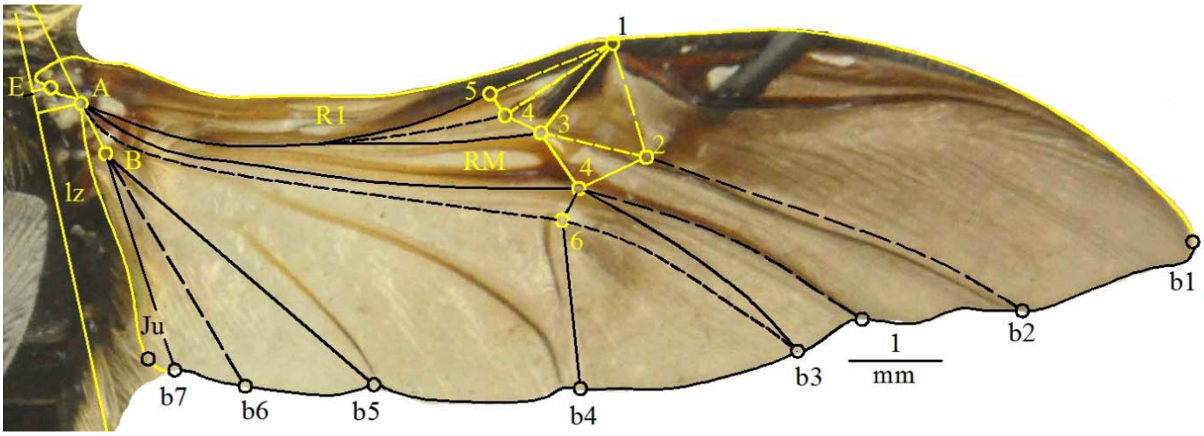


Fig.3. Wing and beetle scheme *Trichius fasciatus* (L.).

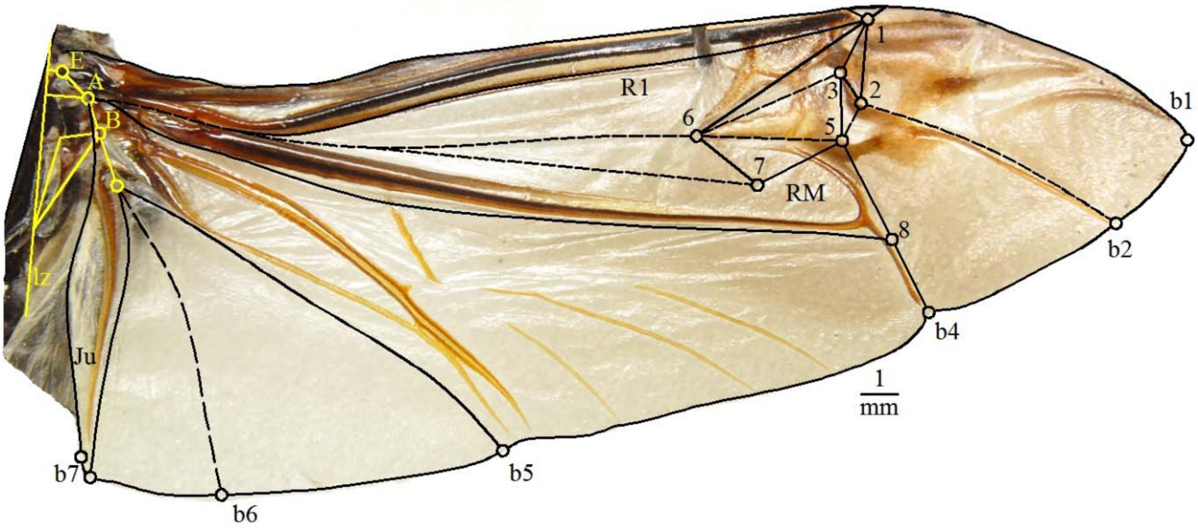


Fig.4. Wing and beetle scheme *Monochamus sartor* F.

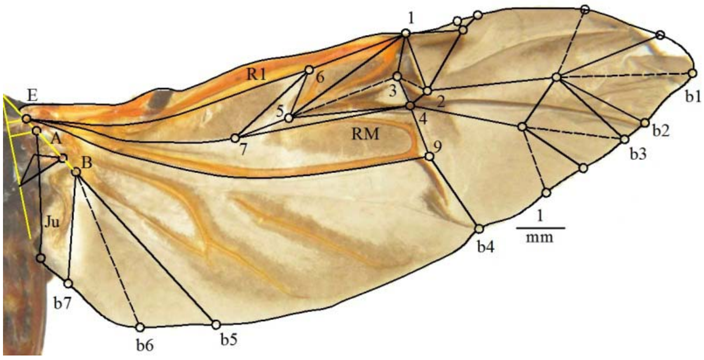
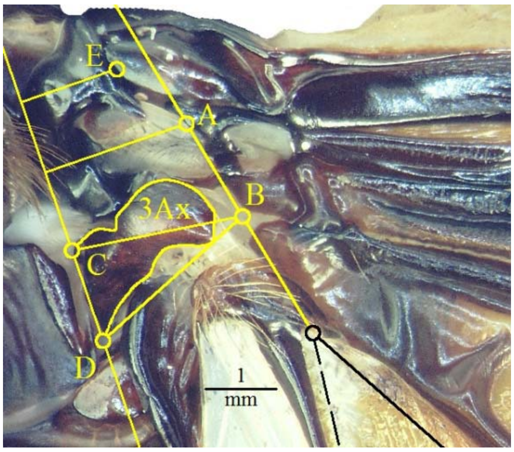


Fig.5. Wing and beetle scheme *Chrysomela populi* (L.).

The wings were shown excluding the jugal part, with indication of the position of the jugal fold (Ju). When folding the wing membrane, the jugal part folds along the jugal fold and is arranged below the anal part (A) on the insect abdomen (Fig.2). The figures below present the (right) wing joints and the adopted structures.



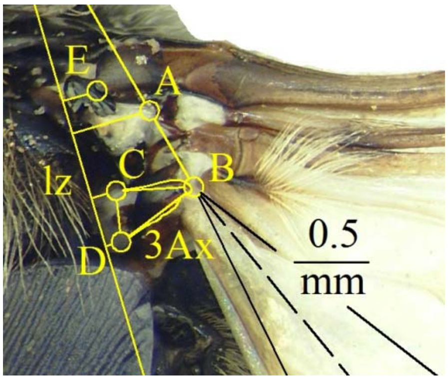


Fig.6. Wing joint and folding pattern of a beetle *Chelorrhina polyphemus* (KRAATZ).

Fig.7. Wing joint and folding pattern of a beetle *Trichius fasciatus* (L.).

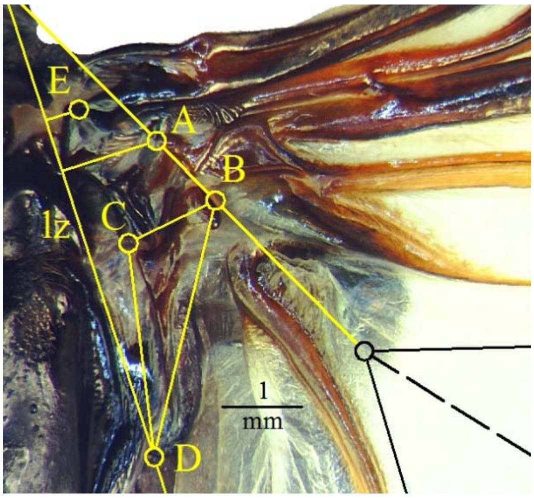


Fig.8. Wing joint and folding pattern of a beetle *Monochamus sartor* F.

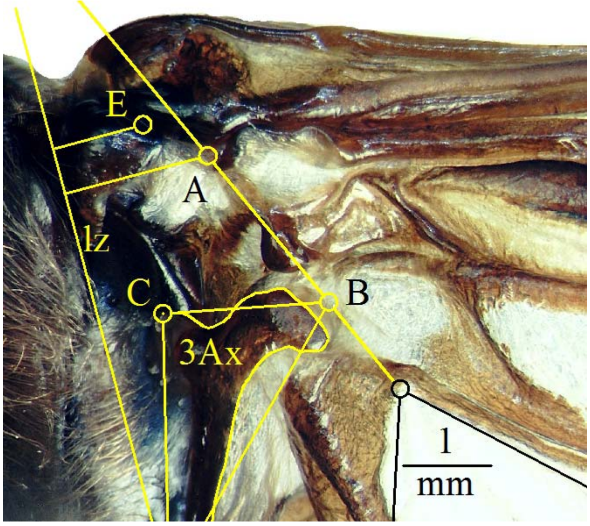


Fig.9. Wing joint and folding pattern of a beetle *Prionus coriarius* (L.).

During the outward wing movement, the leading edge (C+Sc) performs a complex movement. It rotates around its own axis (Geisler *et al*., 2014) with simultaneous rotation around the point A.

Point A is the main center of wing rotation in the wing opening and closing movement. It is located at the base of the radial vein (Figs 6-9) and is associated with the first axillary plate 1Ax. This plate creates two important mechanical joint connections. One of its ends is arranged (but not combined) with the subcostal vein (Sc) at point A, and its wider part connects through the wing joint with the second axillary plate 2Ax (Szwanwicz, 1956).

The A point location is very important for the wing folding along the primary fold 2Ax (line AB, Figs 2-9). It is positioned on the primary fold (basalar, *plica basalis*), which runs obliquely to the insect body axis and is raised together with the 3Ax plate during the wing folding.

Determination of all adopted structure points required observation and recording of all wing movement phases. The maximum wing edge deflection is limited by the insertion of a thickened outgrowth of the Sc vein into the sclerite slot (Fig.11) connected to the 1Ax plate. This system is additionally supported by the hp sclerite surface, which adjoins the first axillary plate and tegula, point E (Figs 6-9). The position of E point was defined as a structure point of contact at a maximum angle of wing deflection. This wedge connection type mechanism was defined as a lock. Locks presented in figures (Figs 10-11) are extremely important in the wing movement.

Inside the locking structure a flexible kinematic pair could be found. It is located between the hpk apex of hp and membranes inside the socket (gn) of the 1Ax plate (Fig.11). This flexible kinematic pair helps to keep the wing locked during its motion relative to the hinge line. This connection acts as a latch. The lock occurs in every observed beetle wing. It allows blocking the wing in the joint plates after the tension of the 3Ax muscle.

The lock sets other internal structures of the wing joint relatively. For simplicity, it was assumed that the lock forms a flat kinematic pair of first class with the rotation axis perpendicular to the surface of the wing. During the wing flapping both the lock and the folding mechanism elements remain motionless. After locking the open wing it is possible to transfer drive from the musculoskeletal system to the wing.

Fig.10. Beetle wing lock mechanism,
Melolontha melolontha (L.).

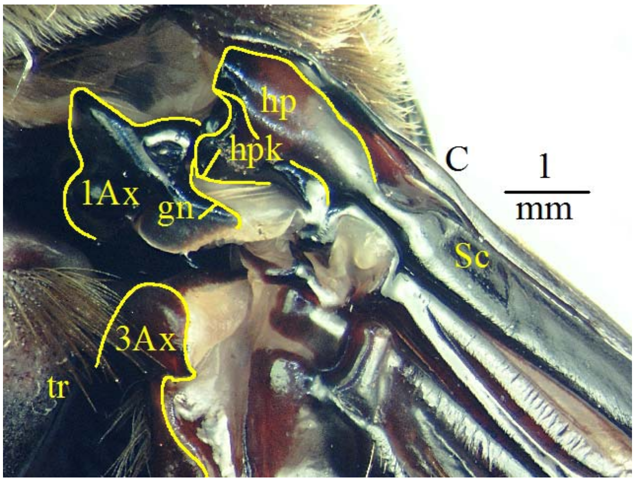


Fig.11. Beetle wing lock mechanism,
Mecynorrhina torquata (F.).

For most of the analyzed wings one or two points on the axis of rotation of the 3Ax plate (C, D) are located on the hinge axis of the whole wing. Point B defines the outer apex of the 3Ax plate. The 3Ax plate is connected with the fundamental ends of anal veins. Using the elastic wing membrane it drags the anal part of the wing, which fits on the insect's abdomen. In the figures presenting the wing joint mechanism, the outline and Ax3 plate points (B, C, D) in top view were marked (Figs 6-9). A wing membrane elastically connects the primary fold and the rest of wing veins. Membrane parts are presented in the wing joint diagram (Fig.12) as triangles CBB' and DBB'.

The shape of the 3Ax plate and the adjacent flexible wing membranes are matched to the shapes of other plates and vein tips converging at the wing joint (Fig.1). It creates an additional support (lock) between the structures of the wing join mechanism and takes away the degrees of freedom during the wing flapping.

4. Mechanism parameters of beetle wings

Defining the mechanism parameters of wings was based on the pictures and an analysis of actual wings of selected beetle species. During the analysis points and planes of movement of the separated internal wing structures (facets) were determined.

Table 1 presents the selected main geometrical parameters of the analyzed mechanism bodies and dimensions of wing mechanisms.

Table 1. Parameters of wings.

Species	α [°]	a [*mm*]	a1 [*mm*]	ab [*mm*]	a12 [*mm*]	a14 [*mm*]
Chelorrhina polyphemus (KRAATZ)	*12.1*	*2.1*	*23.7*	*47.2*	*2.8*	*16.0*
Mecynorrhina torquata (F.)	*8.4*	*2.4*	*26.5*	*51.7*	*3.4*	*17.5*
Eudicella trilineata (QUDENFELD)	*16.6*	*1.9*	*17.0*	*33.5*	*2.5*	*11.1*
Cetonia aurata aurata (L.)	*18.7*	*0.8*	*10.4*	*21.0*	*1.5*	*6.8*
Trichius fasciatus (L.)	*13.7*	*0.5*	*5.7*	*12.0*	*1.3*	*3.7*
Melolontha melolontha (L.)	*26.1*	*1.4*	*15.2*	*26.8*	*2.4*	*9.7*
Aromia moschata (L.)	*36.2*	*0.7*	*20.2*	*23.9*	*1.6*	*4.8*
Monochamus sartor F.	*26.8*	*1.2*	*21.1*	*29.6*	*2.3*	*8.1*
Prionus coriarius (L.)	*24.7*	*1.7*	*12.6*	*16.2*	*1.6*	*4.3*
Geotrupes stercorarius (L.)	*22.1*	*1.2*	*15.4*	*24.6*	*3.0*	*7.4*

The dimensions used in the Tab.1 are described as follows:

- α - angle between hinge line (lz), and the main fold line (AB),
- a – distance between A and hinge line (lz) (regular),
- a1 - distance between A and point 1,
- ab - distance between A and point b1,
- a12 - distance between bending point 1 and point 2,
- a14 - distance between bending point 1 and point b4.

Each beetle type significantly differs in the construction of the wings, particularly in the distribution and the number of wing joint structures.

On the basis of the structure locations diagrams it is possible to determine other parameters of the internal wing mechanisms of all analysed beetles. It is possible to determine the angle of wing (and wings elements) movement in relation to the insect's body. It is also possible to designate the surface of the wings in relation to the total area of the insect and to its weight and other parameters. The parameters determined include the errors arising from the reading and image processing.

5. Structural models of wing mechanisms

As a result of observation the structure of the internal mechanisms wings were separated. Figure 12 presents a general diagram of the wing joint mechanism with designation of main points and wing structures.

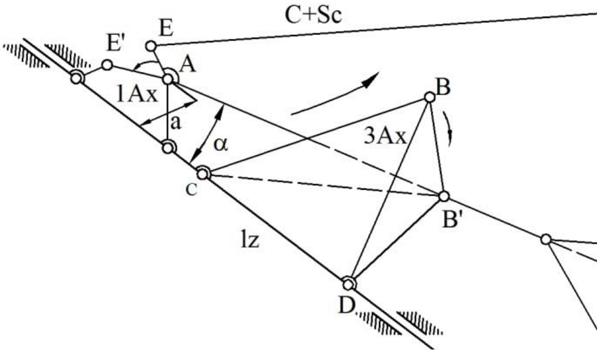


Fig.12. General diagram of beetle wing joint mechanism.

Based on the analysis of the obtained structures of the folding mechanism for beetle *Chelorrhina polyphemus* (KRAATZ) (Fig.2) and other beetles, real models were made. The mechanism with the highest degree of complexity was presented (Fig.13).

The model provides the main functions of the bending joint. Arrows indicate the main directions of wing structures stacking. The diagram was compared to the researched beetle wing using an axonometric view (Fig.14).

It is possible to determine the degree of local mobility of the internal structures for the resulting structure and for other structures. A simplified method of calculation should take into account the presence of kinematic pairs class "I" with one degree of freedom, defined in the work on the theory of machines and mechanisms (Artobolewski, 1988), (Gronowicz *et al.*, 2000), (Miller, 1996), (Felis and Jaworowski, 2007) and other works in the field of TMM.

A triangular facet 1-2-3 which creates a kinematic pair of the first class with the triangle (facet) 2-3-4 along the fold lines 2-3 could be analyzed as an example (Fig.13). The mobility of members can be calculated to identify the type of construction of the wings of different families and types of beetles.

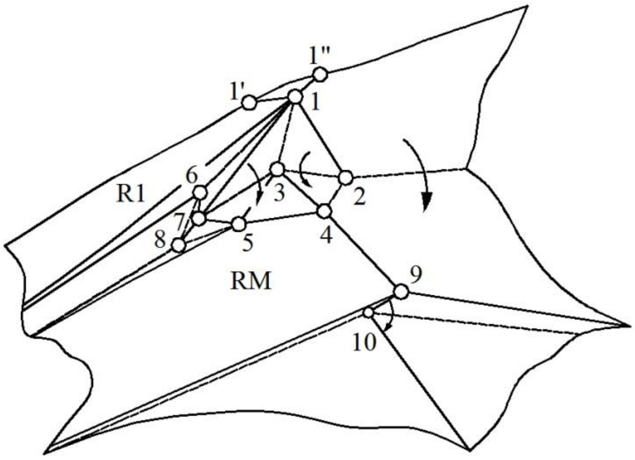


Fig.13. Bending joint diagram of beetle *Chelorrhina polyphemus* (KRAATZ).

Fig.14. Bending joint of beetle *Chelorrhina polyphemus* (KRAATZ).

In order to use this method, it is necessary to analyze the parameters of the structures. The mutual submission angle of the connected structures depends on their side lengths and on the relative position of the structure in the wing. Total mobility increases along with the complexity, the number of triangle structures and other wing components.

The created models required modifications resulting from the accuracy of determining the position of points, the dimensional differences and the elastic connections between wing structures. It is necessary to use areas of local strengthening while creating a bionic wing.

It was confirmed that ribbed vein tip elasticity plays a significant role in wing bending (Haas *et al*., 2000; 2006: Mallesh, 2012). The elasticity of local wing components was also observed.

6. Conclusions

A structural analysis of selected beetle wings concerned the designation of points, spatial facets and planes in the folding and bending joint, as well as other elements of the internal structure of the real insects' wings. The axillary plates and structures in the surface membrane of the wings were analyzed.

The position and functions of mechanically important body mechanisms were determined. The type of interconnections of mechanism bodies of researched wings was defined.

Different beetle species vary in the hind wing construction. The isolated mechanism structures tend to show significant differences in the wing design. This results from wing functions, behavior of a beetle and biology of the insect.

This study demonstrated different kinds of types of construction of beetle wings, which differ not only in the number of internal wing structures, but also in the method and in the degree of complexity of their folding.

A key to the study was to determine the position of the rotation point of the wing opening movement. Both the hinge line and the primary fold were determined in order to define the parameters of wing mechanisms.

The models constructed have shown that the obtained structures suit the design of bending wings of analyzed beetles.

For further analysis and building a MAV (entomopter) it is required to adopt some universal wing design. The model should take into account most of the significant features of the wings construction shown in this work.

The model of insect wings should allow bending and folding movement as well as the drive transmission. During the flying vehicle design it is also important to consider other observed parameters of the wing movement. These are: the angles of movement in different planes for different species of beetles, size and body weight, and flapping frequency and others.

The parameters of wing mechanisms obtained can be used for designing the mechanisms of wing opening and folding in flying entomopter models. Modern materials with properties similar to natural - like shrilk, technologically advanced composites and others can be used in the MAV design.

Further work should include examination of the remaining structures of the wings, especially the wing drive. Research should relate to other families of beetles and other insects to develop and optimize the bionic construction design in order to adopt it in technology.

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