acta mechanica et automatica, vol.8 no.3 (2014), DOI 10.2478/ama-2014-0023

FUNCTIONAL AND STRUCTURAL ANALYSIS OF WING FOLDING MECHANISM BASED ON COCKCHAFER (MELOLONTHA MELOLONTHA)

Tomasz GEISLER[*], **Piotr ROSIKOŃ**[*], **Wojciech SOCHACKI**[*], **Sandra TOPCZEWSKA**[*]

[*]Institute of Mechanics and Machine Design Foundations, Department of Mechanical Engineering and Computer Science,
Częstochowa University of Technology, J.H. Dąbrowskiego 73, 42-201 Częstochowa, Poland

t.geisler@imipkm.pcz.pl, p.rosikon@imipkm.pcz.pl, w.sochacki@imipkm.pcz.pl, s.topczewska@imipkm.pcz.pl

Abstract: Insects are among nature's most nimble flyers. In this paper we present the functional and structural analysis of wing joint mechanism. Detailed action of the axillary plates and their mutual interaction was also described. Because of the small dimensions of the wing joint elements and the limited resolution of the light microscope, the authors used a scanning electron microscope. Based upon the knowledge of working principles of beetle flight apparatus a wing joint mechanism kinematics model has been developed.

Key words: Bionic, Wing, Geometry, Joint, Folding

1. INTRODUCTION

Millions of years of evolution have enabled insects to develop substantial skill both in flight and active control of wing orientation. Long process of formation and profiling functions of individual biological components and their optimization is comparable to multigenerational research, carried out in order to improve the existing mechanism. Interdisciplinary science that includes a structural and functional analysis of living organisms, either for the construction of technical equipment or in order to adapt them in technology, as well as for the research purposes, is bionics.

In recent years there has been an increase in the number of research and literature in the field of bionics, and in particular in number of studies related to the ability of active flight of insects. An example of research work, in which an attempt to tentative reconstruction of the evolutionary pathway to insect flight was made, is paper of Hasenfuss (2008). In the work of Hass and Beutel (2001) functional morphology of insect wings was described.

Attempts of creating wing membrane folding patterns have also been made. The model introduced by Haas and Wootton (1996), included flexagon consisted of four flat facets that converge at a common node. Frantsevich (2011) and Geisler (2012) developed this flexagon pattern idea. Frantsevich (2011) work, apart from analysis of wing cover rotation mechanism in Coleoptera insects, also includes a flexagon model of the Haas and Wootton's type, as well as helical model introduction. Geisler (2012) study presents an analysis of both structure and internal folding and flexing structure mechanism of beetle wings. Both wing structure folding and their reciprocal motions were defined. In addition, in the work of Geisler (2011) the wing structure and folding of selected families of beetles, indicating biological characteristics as well as wings, covers and insect weight correlation, was described.

Intensification of work on creating a mechanically reproduced wing of various insects is also apparent. Efforts to follow the bending movement and the construction of an artificial beetle wing were shown in the work of Muhammad et al. (2009 and 2010). In Bhayu et al. (2010) and Nguyen et al. (2010) publications not only the design of the wing, but also a flying model that mimics the movement of the wings of an insect were presented.

Undoubtedly, the dominant feature of the wing is to allow flight, but some insects evolved also ability to fold and bend some parts of the wings. All these movements are carried out by using wing joint.

Although there is a broad spectrum of work and intensive research in the field of insect flight apparatus, but so far very little was done in regard to the terms of mechanical and kinematic analysis of an important mechanism, which is a combination of wing joint and body of an insect.

The structural composition and functional scope of the individual components of the wing joint are very complex. The aim of this study is to geometrically analyse the properties of wing and body joint, and to create structural model simulating simplified mobility of this connection.

2. GENERAL STRUCTURE AND FUNCTIONS OF FLYING BEETLE WINGS

One of the main features specific to insects, representing the most numerous animal taxa, are wings - diverse in their structure and shape. These structures are a highly specialized flight apparatus, which are tailored to meet the individual demands of different families of insects.

The fully developed wing (Fig. 1) is made of double-layered membrane supported by an exoskeleton constructed of rigid structures and veins. Winged insects (*Pterygota*) usually have two pairs of wings located on middle (*mesothorax*) and the most posterior (*metathorax*) thoratic segment. In the examined beetle families the front pair of wings was transformed into hard covers (elytra). Heavily chitinized covers provide protection for the thorax and second pair of wings. Natural long-chained polymer in the form of chitin is the main component of the exoskeletons of arthropods, which, thanks to strong intermolecular hydrogen bonding, gives increased mechanical strength.

An unquestionable consequence of this evolutionary transformation is a significant increase of flight surface of the hind wings relative to the covers. Moving the locomotor functions to the hind wings, observed by Szwanwicz (1956), is related to this increase. Since the front wings are chitinised and the hind wings flight surface is increased, beetles at rest place their hind wings on dorsal sclerite of a thoracic segment (*notum*), protecting them under the hard elytra. But in order to do this, they must not only bend the second pair of wings, but also fold it due to its significant surface increase relative to the front pair.

Using the wing joint apparatus and bending joint, beetles can spread the wings out, fold and flap.

3. ANATOMICAL AND FUNCTIONAL ANALYSIS OF WING JOINT

The combination of wing to thorax joint is one of the most mechanically complex systems in the body of an insect. According Szwanwicz (1956), one of its primary functions is to allow flapping while simultaneously keeping this motion within strict boundaries. However, the same mechanism also determines the ability of the folding and spreading wings out, which have been developed by some insects.

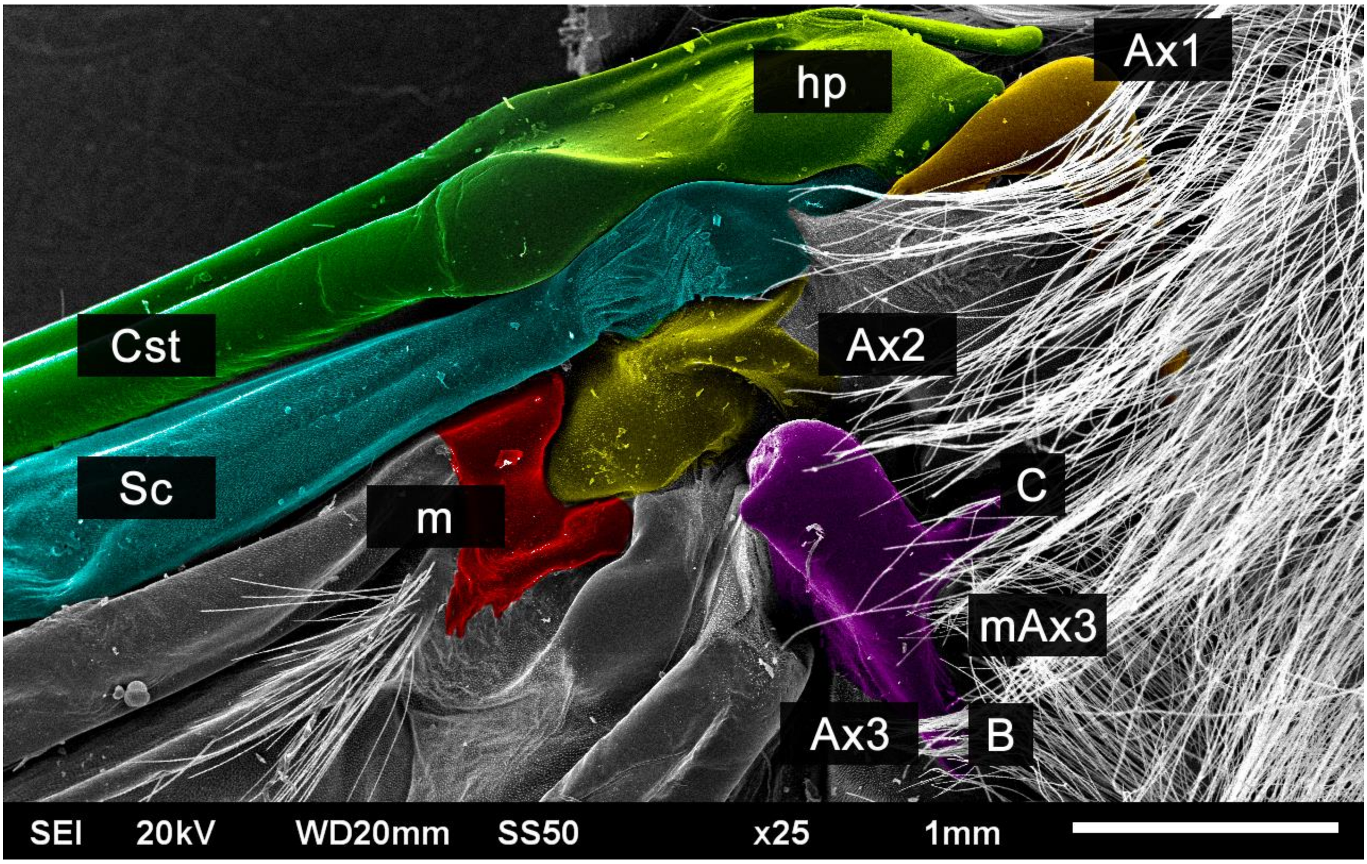

Fig. 1. Beetle wing: Melolontha Melolontha (L.) with separated structural components (individual elements are highlighted). Image was taken with scanning electron microscope

The structural composition and thus the features of axillary apparatus (wing joint) are diversified among the winged insects. This diversity has its basis in a form of adaptation to the prevailing conditions of life, obtaining food or colonizing new areas, typical only for the family of insects. In addition, insects have different mechanisms of changing the size of the wings surface, including different ways of wing folding. Further an anatomical analysis of wing joint on the example of selected species of insect – cockchafer, *Melolontha Melolontha* (L.1758), order: Beetles (*Coloptera*) family: Scarab Beetles (*Scarabaeidae*), subfamily: *Melolonthinae*, genus: *Melolontha* was performed.

From a morphological point of view, wing joint is composed by sclerites in the form of small joint plates, located between the thorax and the veins of insect wings. Sclerite is a hardened body part of an animal. It was formed, originally or secondarily, by separating from the outer product of invertebrate epithelium. It is important that the location of the wing joint lies on the line between the bases of veins and thorax, so that the bases of veins do not reach the insect. Spatial layout of this system is equally important. Wing joint is not a construction build out of closely adjacent elements, but ending at a distance from each other, surrounded by a wing membrane. This very important aspect was described in the work of Szwanwicz (1956).

This allows insects to dispose a great freedom of wing movement, while maintaining the possibility of creating a stable configurations of the internal structures of selected wing functions, i.e. folding, flapping and spreading the wings out. Forming a relatively stable systems allow wings to choose the correct trajectory for selected type of movement, even though the main driving force are the indirect flight muscles according to the conclusions drawn by Dudley (1999) and Szwanwicz (1956).

4. WING STRUCTURE SEPARATION

Because of the small dimensions of the wing joint elements and the limited resolution of the light microscope (4x to 25x), proper structure isolation would be relatively difficult to obtain. Therefore the authors used a scanning electron microscope (JOEL JSM-6610LV), which enables one to record video with a magnification up to 300 000x (with practical application to 100 000x). Biological specimens, such as tissues or tissue components, must first be fixed to preserve their native structure. Hydrated samples, like most biological specimens, must first be dehydrated before placing it in the SEM sample chamber. The wings had therefore been divided into small specimens and prepared for the requirements of the vacuum-imaging environment.

During the analysis a number of internal wing structures were distinguished. For the further analysis three structures S1, S2 and S3 were adopted. The structures division was made on the basis of functional criteria.

4.1. S1 structure

The *Ax1+hp+Cst+Sc* system creates a structure marked as S1 (Fig. 1). Symbols were adopted in accordance with the indications given by Razowski (1987, 1996) and Wotton (1979). If the insect body flexibility is excluded, the *Ax1* sclerite remains firmly attached to the base formed out of the wing segment of insect thorax. One of *Ax1* sides is positioned at the dorsal plate segment of the insect body (*tergum*) and the second, while the wing is unfolded, is combined with *Sc* vein and *hp* sclerite. The *Ax1* sclerite is not situated perpendicular to the longitude axis of the insect body, but it remains tilted at an angle towards the *hp* sclerite. In a location closest to the *hp* sclerite and the *Sc* vein, *Ax1* has a double recess. The *Sc*+*C*st veins are a part of the leading edge of the wing. The *Cst* vein starts next to sclerite described as *hp*, while *Sc* starts with a process coming out of a vein base narrowing.

The S1 structure is used as wing blocking mechanism when it reaches the maximum angle of the leading edge in the outward movement of the wing with respect to the body. During the outward movement, the wing leading edge (*Cst*+*Sc*) rotates around its axis while simultaneously rotating around a point marked as A (Fig. 1). The maximum deflection of the leading edge in the wing plane is determined by inserting an *Sc* vein process into the *Ax1* sclerite recess. This system is additionally supported by the *hp* sclerite surface, which is in linear contact with the *Ax1* sclerite.

4.2. S2 structure

Another separated structure is composed out of Ax3 sclerite and mAx3 muscle. The Ax3 sclerite is shaped similar to triangle, which in the rest position of the wing takes position similar to perpendicular to the longest axis of the insect body. The mAx3 muscle is attached to this sclerite, making it the unique combination of muscle and sclerite in wing and thorax joint.

During the microscopic observation of the folding and spreading out the wings, the axis of *Ax3* sclerite rotation was determined. Rotation axis was described by defining its end points as B and C (Fig. 1). In the unfolded wing position, *mAX3* muscle remained contracted, while *Ax3* sclerite remains close to the veins base, which shows its triangular shape. The process of wing folding is related to *mAx3* muscle length changes, which causes approximation of the edge opposite to the rotation axis (starting from the common vertex B) to the insect's body. Folding and spreading out the wings is also related with tension and relaxation of subalar and basalar muscles.

Rotary movement of *Ax3* sclerite, using attached mAx3 muscle of S2 structure is the mechanism responsible for the folding and spreading out the wings. With the approximation of one of the sclerite edges to the body, veins, the bases of which converge around the axillary apparatus, are also approximated. Thus the wing begins folding process, starting from the jugal area (Ju) that is located nearest to the insects' abdomen.

4.3. S3 structure

Separated S3 structure was analysed based on spread wings prepared to fly. The S3 structure is composed of the elements of the S1 structure (*Ax1*+*C*+*Sc*+*hp*), which were complemented by m and *Ax2* sclerites. The S1 structure, as was written before, allows blocking the wing at maximum deflection angle of the leading edge, while spatially extended *Ax2*+*m* sclerites allow bending of blocked wing.

Having the elements in a specific location and with specific functionality, a structure that allows the wing flapping simultaneously stiffening wing joint, while preserving the limited spatial trajectory of the wings, was obtained. There is a possibility of forcing an additional bending the wing structure; nevertheless it results from the shape and elastic properties of the material of S3 structure components, therefore the system can be considered as rigid.

5. GEOMETRICAL WING ANALYSIS

In order to provide an analytical presentation of insect's wing geometry movement, a Cartesian coordinate system was introduced. Using three mutually perpendicular planes, allowed marking the location of defined points in three-dimensional space.

The origin of the body-fixed Cartesian reference is set at a point located between two preaxillary sclerites: humeral plate (*humeralis*) at the base of the *Cst* vein and tegula (*tegulae*) anterior to the base of *C*st vein and the highest point of *Ax1* element (Fig. 2). Axes were defined as x, y, z.

The x-axis is shifted by the line segment *c* - parallel to auxiliary line *b*, which is the axis of symmetry of the insects longitudinal thorax segment. Both the *xy*-axes and the auxiliary line lie on a horizontal plane α. This plane divides insect at an altitude of the vertical axis so that it runs through the origin of the system while maintaining perpendicularity with reference to this axis. Insect's location, relative to the reference system, is longitudinal in reference to x-axis and in accordance with its direction.

The *a* line was determined from the end of the wing leading edge to the origin of the coordinate system, providing thus a simplified variant of the analyzed edge. Two position of this line were also defined: a_{min} and a_{max} representing the resting position of the wings leading edge and its maximum spread, respectively.

The ω angle indicates the line *a* resting position deviation in respect to the x-axis, while ψ angle indicates its maximum deflection in respect to the a_{min}. The method of line *a* movement is carried out in an arc motion, taking place in two dimensions with the centre of rotation located in the origin of coordinate system. The *a* line displacement, in the range of a_{min} to a_{max}, is accompanied by a local rotation with respect to its own axis. The rotation angle was labelled as φ. As mentioned, trajectory of points belonging to the moving *a* line is not perpendicular to the x-axis. Though it can be visualized as arc shaped points' movement, whose path is partly negative along the z-axis and thus moving below the a plane α. The angle of maximum reduction in the *a* line was labelled as τ.

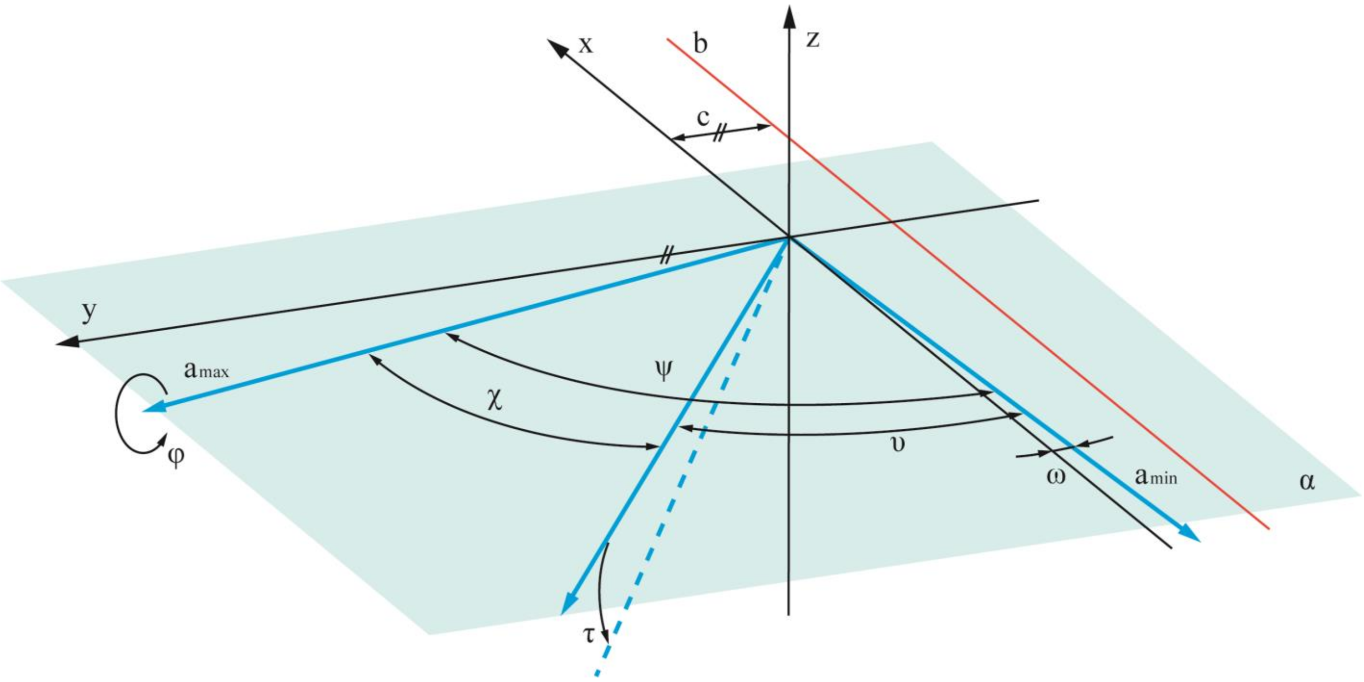

Fig. 2. Cockchafer's wing geometry. Coordinate system was adopted for the left side of insect body

6. RESULTS: KINEMATIC MODEL OF WING FOLDING

The complex wing joint mechanics arise from the high number of components, therefore the authors have defined its functionality using three structures: S1, S2 and S3.

According to Felis et al. (2008), Miller (1996) and Morecki et al. (2002) elementary and rigid components with undivided functionality and with the ability to perform relative movement are referred to as bodies. Therefore one can relate to the S1, S2 and S3 components as bodies.

The detailed action of the axillary plates and their mutual interaction to produce circular wing motion is difficult to describe. Thus, several underlying assumptions must be specified.

Motion may thus be either relative (performed by the axillary plates) or it may be absolute (performed by the separated structures S1, S2 and S3). In what follows, the thorax will be assumed to be at rest and all the motions referred to it will be considered as absolute. In Figs. 3, 4 and 5 the wing is placed along the abdomen (resting wing position), while in Fig. 1 the wing is laterally outspread. Each of these pictures was taken from the same position.

6.1. Structure movement analysis

It was noticed that in order to complete both the outward and the inward wing movement, the local rotation of *Cst* + *Sc* bodies is performed. This assumption is supported by the visibility changes of these components. One may observe that the *Cst* + *Sc* components are highly visible in Fig. 1, whereas they are partially hidden in Fig. 3. In regard to the above and to the fact that both of the images were taken from the same position, one must conclude that local rotation is essential in order to unfold the wing.

The wing opening causes surface contact between the *Ax1* and *hp* bodies. This action "locks" the insect wing, allowing reaching no more than the maximum deflection angle (ψ in Fig. 2) of the wing leading edge (*a* in Fig. 2). This reflects the anatomical limits to the wing motion.

Simultaneously, the furthest segment of the *hp* (in the form of protuberance apex) is inserted into the socket aperture of *Ax1*. It is accomplished through a slide movement. It was noted that the sliding movement character also allows local rotation of the *Cst* + *Sc* bodies.

Taking into account the indirect participation of other structures bodies, *S1* structure action may be described as "locking wedge mechanism". It should be noted that the resilient part of this mechanism allowing pulling the hp apex out of the socket, is implemented directly in the member *mAX3*. Given the nonadjacent spatial distribution of the wing joint and its embedding in the membrane of the wing, it was noticed that other structure members have an indirect role in the transmission of the *mAx3* contraction and relaxation.

A characteristic feature of wedge mechanism is the lack of motor connections, whereas its elements are connected solely by means of sliding pairs. Therefore it was assumed that a flexible kinematic pair is present in the S1 structure, allowing the wedge part to enter and exit the socket part of the mechanism.

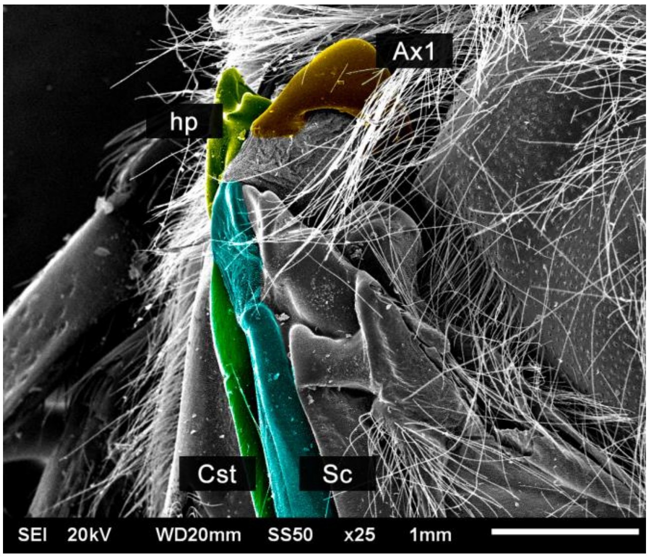

Fig. 3. First structure bodies

The *Ax3* plate rotation is reflected by the S2 elements motions, starting from its triangular position hidden under the thorax (Fig. 4) to a full spread, when its shape resembles a pyramid (Fig. 1). Two points: *B* and *C* (Figs. 1 and 4) define the rotation axis. Rotation is possible due to the adjacent muscle *mAx3* (Figs. 1 and 4) release. Muscle contraction causes the wing folding and hence hiding a part of *Ax3*.

The S2 structure, as a mechanism responsible for the wings folding and unfolding, is a ball joint type mechanism. The S2 structure is also a rotational III-class kinematic pair (lower) and allows the body rotations in the three axes: ψ – wingspread, τ – wing lowering during the folding and unfolding, φ – local wing rotation (Fig. 2). In addition, *mAx2* is a resilient member of the locking wedge mechanism of the S1 structure.

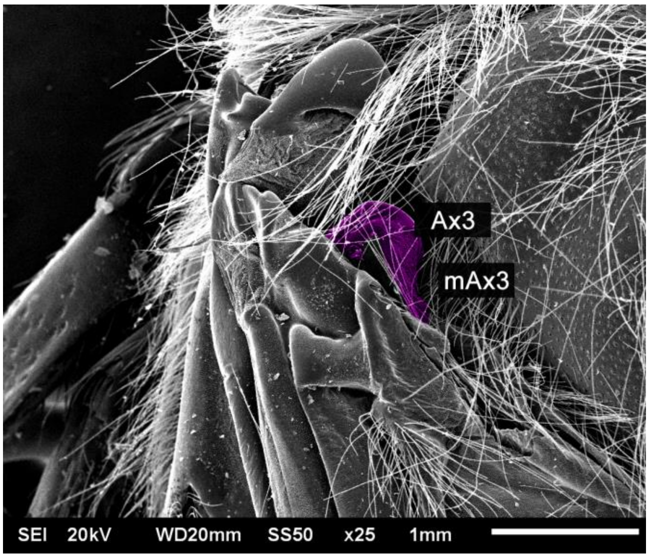

Fig. 4. Second structure bodies

The last of the separated structures marked as S3, is a combination of all S1 structure members and additional two elements: *m* and *Ax2*. The m member, apart of one fixed point, is being significantly shifted during the wing opening movement. Also the *Ax2* body is being slightly shifted and somewhat raised. This allows for the adjustment of both members. "Locking" to the maximum angle of attack and the emplacement of *hp* apex in *Ax1* socket in association with the *m* and *Ax2* movement, stiffens the wing structure so that it could be temporarily treated as a solid plane.

The S3 structure, using the restriction imposed by S1 (ψ – the maximum angle of attack according to the notation of Fig. 2) and taking away the next two degrees of freedom, creates a joint with one degree of freedom of the characteristics of the hinge. This action is particularly important because it allows the wing to work as a single rigid structure, enabling it to perform flapping.

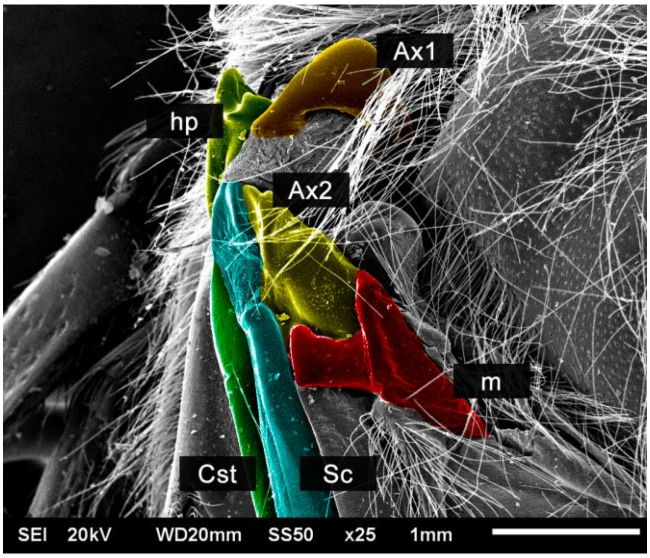

Fig. 5. Third structure bodies

6.2. The flexagon model

The idea of using flexagons as basic figures in the attempt of non-biological imitations of kinematic structures as a flight apparatus is not new.

In geometry, flexagons are complex three-dimensional models, characterized by polygonal surfaces called facets, which are mutually oblique planes. This structure is composed of a material folded in such way that the individual facets reveal themselves only when the structure is bent along the folds. It is possible to create different relative positions of the facets in a flexagon. Flexagonal structures are the basis for models described in the work of Frantsevich (2011) and Geisler (2012).

Based on the geometric, structural and kinematic wing joint analysis, the flexagon model (Fig. 6) was proposed as a solution for the flight apparatus movement implementation of the selected insect. It could be assumed that this model could be also applied for other beetle families that fold wings.

The facets (or a combination of facets) derive from the components of the S1, S2 and S3 structures. They are to be mechanical equivalents of the biological structures. It is therefore assumed that:

- Facet BCD is stationary;
- Facet BDE is the equivalent of the Ax3 plate, wherein the BD section is a rotation axis corresponding to the BC section of Fig. 1;
- Facets ABW+AHW are the equivalents of the *Ax2* plate;

- Facets EFW+FGW+GHW re the equivalents of the *m* plate;
- Broken lines indicate downward edges.

It was assumed that the points A and B are rigidly mounted to the leading edge of the wing, while the leading edge is parallel to the straight line between these points.

One of the main movements performed by the wing is unfolding. Given the fact that the direct force only acts on a rotating facet BDE, it is necessary to transfer this power to the leading edge through intermediary facets. Rest position of the BDE facet is associated with the right angle (δ in Fig. 6) relative to the BCD facet. The unfolding is related with an increase of this angle. The springiness of the material enables returning to the starting position without "passing through" the dead centre position.

Due to the movement of the BDE facet, the change of BEG and ABG facets is forced. BEG facet changes its initial angle (90°) relative to the ABG facet striving to achieve an obtuse angle. However ABG facet rotates in such a way that the BG segment is directed towards the BD segment.

The primary function of wings is to allow translocation by flight, pursued by the flapping. This movement was mechanically described as a hinge movement. The BDE facet of the proposed model (Fig. 6, point c) creates a fixed base, so that it becomes a pair of hinge.

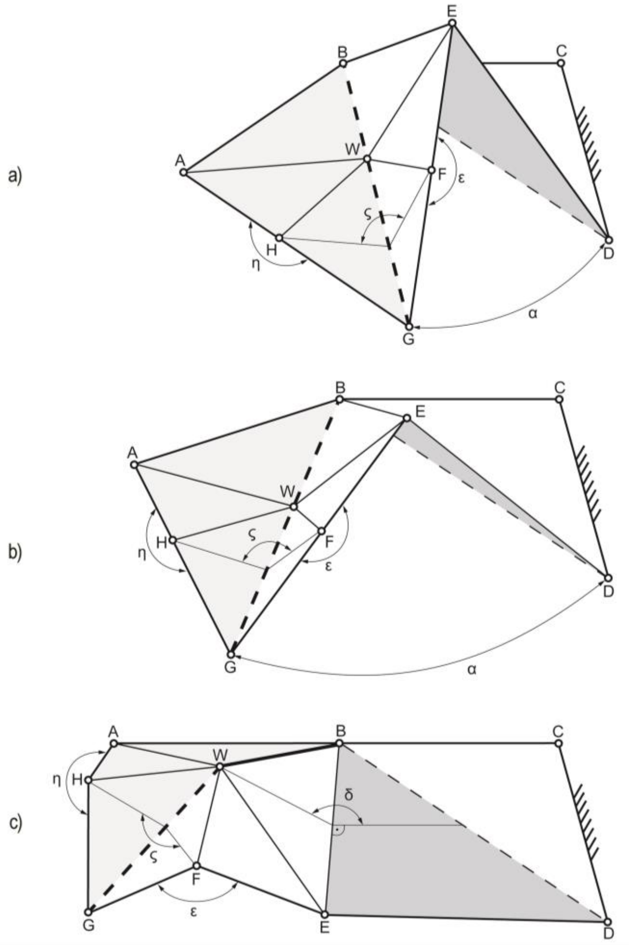

Fig. 6. Geometry and unfolding of proposed flexagon model

It became necessary to introduce such stiffen of the structures restricted by ABEG points, that could prevent structure folding while the movements of the hinge pair (wing flapping). The solution is the spatialization of model planes segments, implemented by lowering GHW and FGW facets. The W point that is the common vertex of facetes restricted by ABEG points is being raised. The ABW, AHW and BEW converge externally in the vertex W. The common edge GW of facets FGW and GHW is directed downwards thereby prevents free mutual "breaking" of the structures. The wing must remain forced open.

The structures spatialization should meet the requirements of angles and lengths of the individual structures edges compatibility. Moreover, in the case of non-parallel structures the internal angle of collapsible structures will be determined by specifying the angle range.

It is possible to change the vertex position and to adapt new facets proportions or to increase their number. The proposed system provides a basis for further analysis and better representations of the wing components composition.

6.3. The scheme of flexagonal model

During the wing joint kinematics research, the anatomical and functional analysis as well as the wing structures separation were performed. The wing geometry was also described. The simplified motion model was based on the flexagonal model, which could be reduced to the planar mechanism with a kinematic pair of first class.

The kinematics model (Fig. 7) includes the wing movement in the range from rest to operating position.

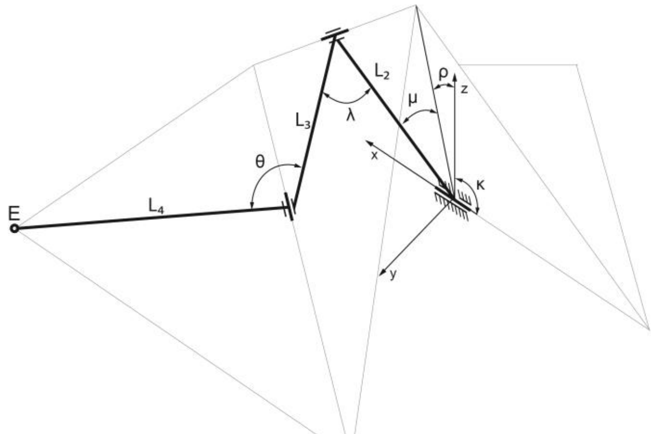

Fig. 7. Model of the kinematics

The kinematic chain consists of three moving bodies and one fixed body (three kinematic pairs of I-class). The auxiliary angle ρ takes the value between 0° – 80° (90°). In the particular case the μ angle is constant and amounts to 45°. The λ angle takes the value in the range of 0° – 170°(180°), while the θ angle is between 90° – 170° (180°). The E point position is the vector sum of L_2, L_3 and L_4 in the adopted coordinate system.

The number of freedom degrees is given by the planar chain mobility formula:

$$W = 3(n_c - 1) - \sum_{i=1}^{2}(3 - i)p_i \tag{1}$$

where: n_c – total number of joints, p_i – kinematics pairs.

The given number of freedom degrees equals 3 in accordance with the actual system. The facet shape imposes the position of the axis of rotation between the separated bodies of the kinematic chain.

7. CONCLUSIONS

Biomimetic engineering is an effective design approach, therefore future research may be oriented to creating a mechanical models based on extensive kinematic. Flapping wing mechanisms may be implemented in the micro air vehicles (MAV's).

Flight behaviour of insects is closely connected with their mechanical properties. This study provides geometric and functional basis of the insect's wing joint.

In order to carry out this analysis, the authors used not only the light microscope but also an scanning electron microscope. On the basis of the microscopic observation, a number of key wing structures were isolated and described in mechanical terms. Studies on the kinematic pairs in the wing mechanisms were also carried out.

The authors made an attempt at applying the results of geometric and functional analysis to a flexagonal model that would mimic the flight apparatus motions of Melolontha Melolontha. The created model is designed based on the working principles of the axillary plates mutual movement and meets the anatomical limits of the beetle's wing motion.

REFERENCES

1. **Bhayu P.R., Nguyen Q.V., Park H.C., Goo N.S, Byun D.** (2010), Artificial Cambered-Wing for a Beetle-Mimicking Flapper, *Journal of Bionic Engineering*, Vol. 7, 130–136.
2. **Dudley R.** (1999), *The Biomechanics of Insect Flight: Form, Function, Evolution*, Princeston University Press, New Jersey.
3. **Felis J., Jaworowski H., Cieślik J.** (2008), *Analiza Mechanizmów*, t.1, Wyd. 2, Wydawnictwa AGH, Kraków.
4. **Frantsevich L.** (2011), *Mechanisms Modeling the Double Rotation of the Elytra in Beetles (Coleoptera)*, Journal of Bionic Engineering, Vol. 8, 395–405.
5. **Geisler T.** (2011), Beetle wing construction and folding of selected families (Coleoptera), Biuletyn Częstochowskiego Koła Entomologicznego, Nr 10 11/2011, 12-21, (in Polish).
6. **Geisler T.** (2012), *Analysis of the structure and mechanism of wing folding and flexion in Xylotrupes Gideon beetle (L.1267 Coleoptera, Scarabaeidae)*, Acta mechanica et automatica, Vol. 6, 37-44.
7. **Gronowicz A., Miller S., Twaróg W.** (2000), Theory of machines and mechanisms. A set of analysis and design problems, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław, (in Polish).
8. **Haas F, Wootton R. J.** (1996), *Two basic mechanism in insect wing folding*, Proceedings of the Royal Society B: Biological Sciences, Vol. 263, 1651–1558.
9. **Haas F., Beutel R.G** (2001), *Wing folding and the functional morphology of the wing base in Coleoptera*, Zoology, Vol. 104, 123 – 141.
10. **Hasenfuss I**. (2008), *The evolutionary pathway to flight - a Tentative Reconstruction, Arthropod Systematics & Phylogeny*, Vol. 66, 19-35.
11. **Miller S.** (1988), *Kinematic systems. Design basics*, Wydawnictwo Naukowo – Techniczne, Warszawa, (in Polish).
12. **Miller S**. (1996), *Theory of machines and mechanisms: analysis of physical systems*, Wyd. 2, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław, (in Polish).
13. **Morecki A., Knapczyk J., Kędzior K.** (2002), *Theory of mechanisms and manipulators. Fundamentals and application examples in practice*, Wydawnictwa Naukowo – Techniczne, Warszawa, (in Polish).
14. **Muhammad A., Nguyen Q.V., Park H.C., Hwang D.Y., Byun D., Goo N.S.** (2010), *Improvement of Artificial Foldable Wing Models by Mimicking the Unfolding/Folding Mechanism of a Beetle Hind Wing*, Journal of Bionic Engineering, Vol. 7, 134-141.
15. **Muhammad A., Park H.C., Hwang D.Y., Byun D., Goo N.S.** (2009), *Mimicking unfolding motion of a beetle hind wing*, Chinese Science Bulletin, Vol. 54, 2416 – 2424.
16. **Nguyen Q.V., Park H.C., Goo N.S., Byun D.** (2010), *Characteristics of a Beetle's Free Flight and a Flapping-Wing System that Mimics Beetle Flight*, Journal of Bionic Engineering, Vol. 7, 77-86.
17. **Razowski J.** (1987), *Etymological dictionary*, PWN, Warszawa, (in Polish).
18. **Razowski J**. (1996), *Dictionary of insect morphology*, PWN, Warszawa – Kraków, (in Polish).
19. **Szwanwicz B.** (1956), *General entomology*, PWRiL, Warszawa, (in Polish).
20. **Wootton R. J.** (1979), *Function, homology and terminology in insects wing*s, Systematic Entomology, Vol. 4, 81-93.

List of Acronyms: Ax1 – first axillary plate, Ax2 – second axillary plate, Ax3 – third axillary plate, Cst – costal vein, hp – humeral plate, m – median plates, mAx3 – third axillary plate muscle attachment, Sc – subcostal vein.