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The Motion Analysis of Attacus Atlas Rigid Wing

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Abstract – *The remarkable aerodynamic efficiency of flapping insect wings has fascinated researchers for many years. Butterfly wings are distinguished by a much larger lifting surface, and thus, a different style of flapping flight. The considerations described in the article are an introduction to a fully flexible analysis of the wing in motion. The study of the rigid wing gives the basic knowledge necessary in the further process. The yaw, pitch and roll angles obtained from the footage have been used to analyze the rigid wing. The data has been adapted to CFD calculations in Ansys Fluent software along with the geometry of the joined wings (one surface on one side). The wing deformations have not been taken into account during the analysis. The obtained results make it possible to specify clearly the aerodynamic forces in three directions and the pressure distributions on the wing surface. For a rigid wing, there is positive drag and negative lift. The negative lift indicates the exceptional importance of wing deformation, which is the only guarantee of the insect's ability to fly. On the other hand, a positive drag is evidence of the influence of the shape of the bearing surface on the flow aerodynamics.*

Keywords*: Attacus Atlas, Flapping Flight, CFD, Rigid Wing*

Nomenclature

CFD	Computational Fluid Dynamics
l	Wing length
p	Pressure
Re	Reynolds number
u	Wing tip velocity
u_{bd}	Velocity at the boundary
u_s	Velocity of the solid
ρ	Fluid density
υ	Kinematic viscosity

I. Introduction

The remarkable aerodynamic efficiency of flapping insect wings has fascinated researchers for many years. It has now become an anecdote that, according to calculations using classic aircraft aerodynamics models, a bumblebee should not be able to fly, since it is too heavy and its wings are too small. One of the first significant publications that attempted to explain the key issues related with the aerodynamics of flapping insect wings has been a series of six articles by prof. C. Ellington published in Philosophical Transactions of Royal Society B - Biological Sciences under a collective title: “The aerodynamics of hovering insect flight” [1].

The authors thoroughly describe the phases of an insect's wing during a flapping flight, relating this motion to the motion characteristics of bat and hummingbird wings. In the aforementioned cycle of papers, Ellington explains the vortical nature of flapping wings and the impact of vorticity on aerodynamic forces generated in the course of a flapping flight. He derives a number of relationships that enable, among others, calculating the lift force, and he presents mathematical models for insect wing motion kinematics. He also provides tables with significant mechanical values specific to individual species of flying animals.

[2] is an example of a paper devoted to the issue of butterfly wing kinematics and aerodynamics. Its authors describe wing motion using two vectors (for the front and rear wing). These vectors begin at the point where the wing is embedded and end at the point of the wing's contour farthest from the root of the wing. Owing to such a way of describing the position of each wing, it is possible to approximate the angles of attack of individual wing sections. The description has not covered wing deformations or insect in-flight position. It should be noted that the angle of attack in butterflies’ wings directly implies that their lifting surfaces undergo deformation. This phenomenon does not occur in insects such as flies, wasps, or bees. In [3], Fry, Sayaman and Dickinson have presented insect flight research results (on the example of a Drosophila melanogaster fruit fly).

The studies have been conducted using high-speed cameras. Three cameras have been used since the fly has not been tethered, and its motion could not be repeated.

This has enabled obtaining data on the movement of the insect and its spatial position. The authors have distinguished three flapping wing motion phases, beat, break- off and rotation, while noting that the wing motion in each insect is a species feature.

In [4], Faruque and Humbert have also described observations of fly free flight within a 63 confined space,

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based on the use of three high-speed cameras. In [5], Lin Du and Xiaofeng Sun proffer a two-dimension numerical analysis of a fly wing, while, at the same time, indicating fluctuations of aerodynamic forces at low flapping frequencies, followed by a decline in the amplitudes together with increasing beating frequency. The authors have depicted wing position changes mainly using angles. [6] has presented a series of studies of displacements, as well as forces and torques acting on the wings of the Idea leuconoe butterfly in flapping flight.

The authors have stated that the mass of the abdomen is equal to approximately 40% of the entire insect's weight and its motion on the forces and force torque controlling the motion of the entire butterfly has been taken into account. In the article, the authors have applied a quasi-steady state blade-element model in order to calculate wing aerodynamic forces, dividing each wing into 20 elements. As a result of the conducted analyses and calculations, the authors of this paper have proffered displacement graphs for body end and the wing ends as a function of time. These are characterized by high repeatability.

The analysis discussed in [7] has indicated that the lift force in a fly is generated mainly in the course of wing motion downwards and the thrust during wing motion upwards. Furthermore, in butterflies, the wings meet in the upper position first at the front, followed by the other parts of the wing, from front to back, generating something called the "pumping effect". The wings start spreading from the front with the largest driving force generated at this moment. This enables an increase in thrust by up to 40%. It should be noted that butterflies are classified as insects with low beat frequency, large area, and span of the wings [8]. A butterfly flapping wing laminar flow Reynolds number is in the order of 104.

Butterfly wing beat frequency is significantly lower than the flapping frequency in two-winged insects (e.g., flies, wasps, or bees). Based on analyzing the source literature data, the authors of [8] have stated that a butterfly flying forward always flaps, while combining flapping with gliding, in order to improve flight efficiency. They have considered gliding as an important element of a butterfly's flight, which utilizes vortices generated by flapping. In order to prove this thesis, the authors have visualized vortices in a smoke tunnel, around the models of Papilio ulysses and Danaus plexippus butterflies. Experimental studies of vortex structures generated by the wings of a Papilio ulysses have been also reviewed in [9].

The fundamental elaboration seen in [10] covers the analyses of aerodynamics of a flapping flight in birds, bats and insects. In [11], Makoto Iima has reported that insects use vortices generated by flapping, owing to which they generate a larger lift force than the one estimated by ordinary aerodynamic theory. In addition, based on numerical simulations, the author has attempted to explain the significance of center of mass motion to the nature of flight. Two flight types have been distinguished, namely, steady flight with oscillating center of mass speed and transient flight with irregular center of mass speed changes. He has also tried to define motion parameters at which hovering occurs.

The authors of [12] has discussed the relationships between specific wing geometry and inflight behavior.

Particular attention has been drawn to the so-called "swallow tail" of a Papilio xuthus butterfly. Srygley and Thomas [13] have studied the free-flight of a Vanessa Atalanta butterfly in a wind tunnel. Their tests have involved the method of visualizing flow using smoke.

The conducted researches indicate two occurring types of vortices, namely, active and inactive. Together with wing rotation mechanisms such as clapping (joining in the upper motion phase) and ejection (sudden forward motion), these vortices are used for generating lift force at take-off, landing, and maneuvering.

In [14], Senda et al. have calculated aerodynamic force by applying a model composed of numerous rigid elements, and have compared the results with a force measured in the course of the experiment. The authors of this paper have presented the results of studies involving the aerodynamics of a flapping butterfly's flight, with particular emphasis on analysing free vortices generated by the wing movements. The flapping mechanism has been identified owing to anatomic observation and knowledge of the musculoskeletal system. This enables recognizing the available wing motions of living butterflies. They have constructed an experimental system with a low-speed wind tunnel. As a result, the researchers have recreated wing motion and measured the aerodynamic forces of actual wings. This has been followed by constructing a 3D mathematical model. Its validity and accuracy have been verified by comparing the calculations with the results of experimental tests.

The outcome of this endeavor has been that periodic flapping flight has been executed by using the obtained model. The modelling shows that free vortices in the traces, induced by flapping and resulting from structural flexibility (wing twisting), affect significantly flapping flight stability.

Researchers have also used panel models to calculate the aerodynamic forces of flapping wings. A two-dimension analysis of flexible wing flow has been presented in [15], where the authors have attempted to show that wing flexibility leads to increases in its lift force. A 3D analysis of vortex structures in an insect's flapping wing has been presented in [16]. Here, the authors have assumed that wing area is fixed; hence their silhouette is greatly simplified. The simulations have been conducted with Finite-Volume CFD OpenFOAM solver, using a radially moving grid.

A simplified motion of a flapping wing has been analyzed in [17]. The aforementioned paper presents 2D and 3D numerical analyses of a simplified wing model with flow at various leading edges. Fluid Structure Interaction (FSI) analyses have been discussed in [18].

FSI calculations have been conducted for schematically nerved wings with an arbitrarily adopted geometry. The venation has been aimed at reproducing a different stiffness of the leading edge and trailing edge.

The authors of that publication have evidenced the direct impact of flapping frequency on aerodynamic forces.

Because a part of wing motion in insects is automatic and does not require a nerve impulse, flapping frequency is higher than the frequency of nerve impulses. Madejski [19] and Dudley [20] have stated that butterfly wing motion frequency falls in the range of 10-20 Hz. The studies on the role of internal venation of Papillio butterfly wing show that a wing without venation is characterized by lower drag, yet the lift force in such a wing is significantly lower [20], [19]. Venation stiffens the lifting surface, without depriving it of flexibility, while stabilizing flight. At the same time, venation has a nutritional function, supplying blood and oxygen through trachea [21], [22], [19].

Biej-Bijenko [21] has considered butterflies as belonging to a group of functionally double winged insects, since during flight, the rear pair remains connected with the front pair and they work together as a single surface. The author has described three groups of butterflies, Jugatae, Frenatae and the one represented by Papilionidae, which contains three types of hooks between wings. Jugata (lower butterfly groups) have a narrow zygomatic protrusion at the edge of the front wing that hooks it together with the rear wing. Frenatae (higher groups) have a frenulum on the front wing, which hooks the rear wing via a membranous appendage or a group of bristles. In contrast, in a certain group, among others, the Papilionidae, the role of the hook is fulfilled by overlapping wings.

The leading edge in butterflies is often reinforced with venation shifted towards the edge. Transverse veins disappear, while longitudinal ones interconnect and multiply (polymerization). [22] is a compendium of knowledge on insects, including their structure, taking into account muscle location. However, [23] is a collection of information on the structures of biological materials. Because the review of biological materials is comprehensive and extensive, some of these are approached in less detail. It should be added that previous researches in the field of material science primarily concern the structure of insect wings, and not their strength parameters. Moreover, while the wing structure has been studied by scientists from various scientific domains [24]-[35], the majority of the studies discussed in the aforementioned research work have not led to obtaining reliable mechanical parameters. Studying the mechanical parameters of insect wings is difficult because such wings are made of natural composites and are anisotropic materials.

Essentially, the information required for the purposes of this work is that wings consist of venation that acts as the structure while membranes stretch in between. Such veins are also arranged in an irregular pattern (not along, not across, sometimes almost radially) [26]. Furthermore, each vein has a slightly different structure.

Individual features are also important. In the case of large wings, it is possible to study a specific wing section, while small wings must be tested as a whole, without zoning. This is due to the need to develop a specific, non-universal testing machine for measuring small deformations and small forces. In addition, non-standard devices for bending samples with a length of several or a dozen or so millimeters and a very sensitive measuring system with a range of very low forces are also required. This is due to the measurement possibilities.

In [31], Jiyu Sun and Bharat Bhushan have described the structure of a dragonfly’s wing. In it, a series of cross-section photographs has been revealed, each one depicting a different distance from the insect’s body. A table with such mechanical properties as Young’s modulus and hardness of various wing elements is included within the work.

Currently, this is the only such comprehensive data source and it only applies to one order of insects. In addition, the values vary greatly, depending on the wing element and measurement method. They have been tested with a nanoindenter, which uses a diamond indenter to determine mechanical properties and specifies characteristics based on nanohardness measurements.

Insect wings, as a natural composite, are of very complex structure. This is why determining wing properties based on the properties of constituent materials, without the impact of reinforcement arrangement and its shape, leads to large discrepancies with regard to the actual mechanical properties of the wings. Nevertheless, the mentioned data can constitute a reference point and enable verifying the correctness of conducted studies. The Attacus atlas has been selected as the research subject for the purposes of this work. This insect can be naturally found in South Asia (China, Indonesia, Malaysia, Ceylon) and is the largest representative of the Lepidoptera. Its significant wing area and low flapping frequency constitute optimal test conditions. In addition, the greater the wing area is, the lower the flap frequency is. Hence, observations are easier and more reliable and conclusions are more accurate. It is essential for a given specimen to be bred and that studying it does not require approval from a bioethical committee. The mechanical properties of this butterfly’s wings have been studied in [36].

This paper raises the question of the flapping flight specifics of Attacus atlas butterfly. This article is a first part of complex analysis and mainly contains informations respecting rigid wings of this moth species.

The influence analysis of object shape on the behavior of the flow is of great importance for more complex calculations and must be prepare earlier.

The following parts of the article focus on the successive activities. The first parts deal with the subject of the input data source. The data has been obtained from an experiment performed on a live insect. The next stage described has been the processing of the obtained numerical data and the formulation of a mathematical description for the individual parts of the movement. The actual experiment includes the computation of the non-deformable wing phenomenon and starts with the preparation of the mesh and the input data for the computational software. Finally, the results of the research have been presented, analyzed, and considered as to their suitability for future, more complex calculations.

II. Materials and Methods

II.1. Experiment Description

The first stage of the experiment has consisted in building a test stand allowing filming the motion of the wings of a stationary insect of Attacus atlas species. The test stand has been placed in a wind tunnel of the Division of Aerodynamics of Warsaw University of Technology.

The insect has been fixed to a plastic U-bar with a zip-tie located behind its wings, which has allowed freeing it easily after completing the experiment. The other end of the U-bar has been placed in a vice. Due to the weight and strength of the insect, it has been impossible to glue it on (in similar experiments a glue intended for use on animals has been applied) [37], [38].

Wing motion has been filmed simultaneously from three sides, with three cameras: from the back, from the side and from the bottom, using Photron SAZ with Nikon 50 lens, Photron SA5 with Nikon 50 lens and Photron SA1.1 with Nikon 35 lens, respectively. Such a set-up (Fig. 1) has allowed simultaneous tracking of the motion in three dimensions. Shots have been taken with the frequency of 5,000 frames per second.

For research purpose, zero velocity of the air-flow in the wind tunnel has been assumed. Any velocity generated by the tunnel had an adverse effect on the insect placed in the tunnel. The insect perceives it as an external threat and does not make any wing movement, attempting at the same time to maintain its current position. Nevertheless, the location of the test stand in a wind tunnel has been justified since it has enabled isolating the experiment zone from the external disturbances of the airflow, vents, drafts, etc., ensuring that they have not influenced the wing motion. The cameras have been turned on simultaneously, because they have been connected with a single common trigger. Thus, the position of wings on particular frames with the same number is identical in shots taken from different sides.

Since calculations described in this paper apply to a stiff wing, it is necessary to precise that maximum upper and lower deflection of the wing is of utmost importance.

II.2. Data Analysis

Since the butterfly wing structure consists of small scales that are visible under a microscope, it has been impossible to apply any physical markers neither in the form of adhesive points nor using paint (Fig. 2).

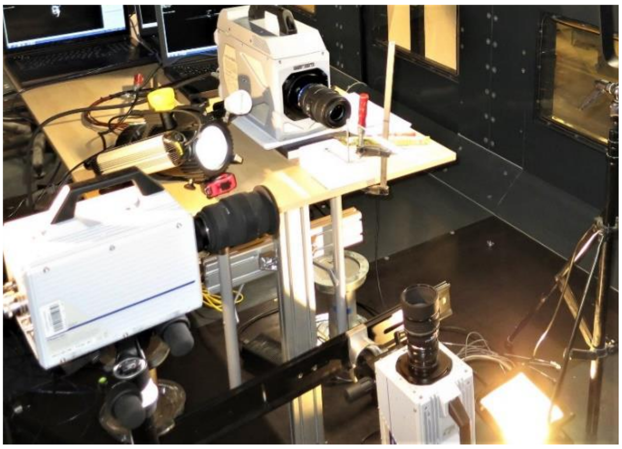


Fig. 1. Research stand and facility

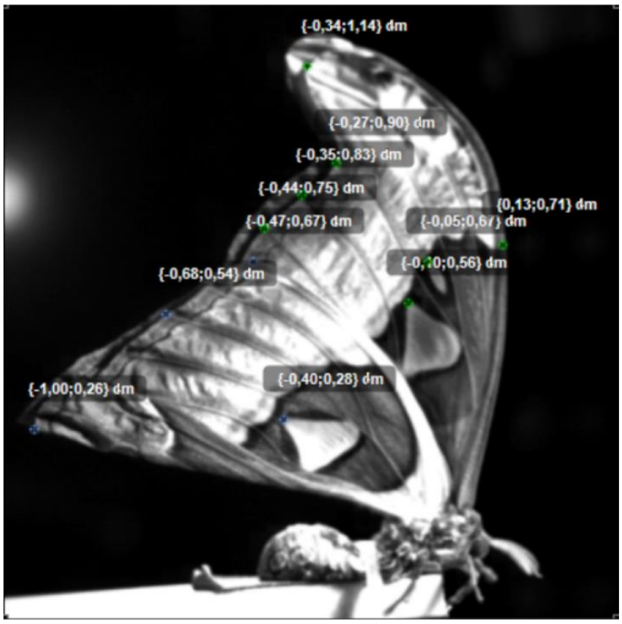


Fig. 2. The location of the markers

Points on a wing have been superimposed on a frame with Kinovea software in a virtual manner using a natural drawing on a wing and points characteristic for its structure.

Only right wing points have been tracked, assuming that the left wing moves in a similar way and the whole motion is marked by symmetry. In total, eleven virtual points have been superimposed. Seven of them have been placed on the forewing and the rest of them on a hindwing. At the same time, forewing and hindwing have been treated as a single lift surface [21].

Therefore, the term “wing” used in the further sections of the paper refers to the whole lift surface. The points have been labelled with letters, omitting the letter “l” (in order to avoid misunderstandings).

Further on, calibration has been conducted in the aforementioned software using the known values consisting in the dimensions of the U-bar. After calibration, the motion tracking of the points in time has been initiated.

This has required an introduction of manual adjustments, since the software has not always recognized the points due to the lack of color and high dynamics of the motion. During the motion tracking process, it has also transpired that a series of shots taken from the bottom has not provided the necessary data, because in the clapping phase, the wings have been obscured by the large body of the insect. In spite of that, shots taken from the side and from the back have provided sufficient information in order to re-create the dislocation of the points in 3D in the Cartesian set of coordinates whose center point is located in the body of the insect, whilst X-axis conforms to the direction of flight, Y-axis is directed upwards and Z-axis is directed to the right (Fig. 3). Thus, the following sets of data have been assumed in the spatial coordinate system:

- For the X-axis, a series of coordinates on X axis direction in side view,
- For the Y-axis, a series of coordinates on Y axis direction in side view,
- For the Z-axis, a series of coordinates on X axis direction in back view.

The next stage has consisted in operations on the data sets: 3 coordinates in 912 positions of the wing during a single stroke for each of the 11 points. In total, this yields over 30,000 data items. At the same time, it can be calculated that the wing stroke frequency is approximately 5.5 Hz.

Such a low frequency of the flap allows an examination of the phenomenon that is more precise. In fact, this has been the reason why such a large insect has been used in the experiment. The larger size of an insect translates into lower frequency of the wing stroke and makes the deformations easier to observe.

After the data have been exported into a spreadsheet, a set of characteristics has been created. Next, this set has been smoothed using a moving average with a variable shift in order to fit elastically the courses to previously obtained data [37], [39], [40].

This set of data describes the deformation of the wing during the motion in a relatively detailed way. However, as mentioned earlier, for the needs of calculations describing only the flow of a stiff wing, it has been only necessary to apply the angles of maximum deflection and the frequency of the flap.

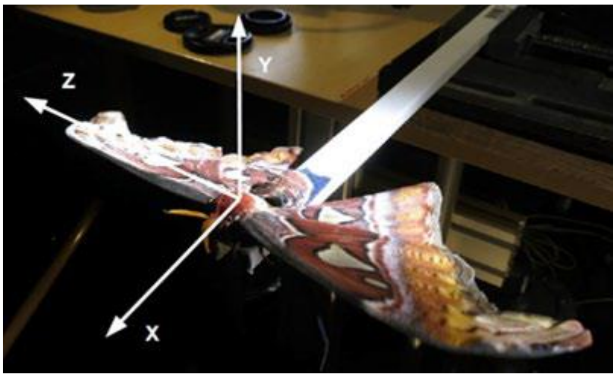


Fig. 3. Coordinate system adopted

To that end, the coordinates of point A (describing the position of the apex of the wing) of maximum and minimum Y value (-89,34; 3,66) have been taken. Next, the angles of upward and downward wing deflection have been calculated.

The subsequent step has consisted in matching a sinusoidal function describing the change of the deflection angle during a single stroke (one full cycle) of a wing.

The following functions have been assumed:

$$x = [1; 378] \rightarrow y = 46{,}5 \times$$
$$\times \sin\big(0{,}0083331(x + 187{,}5)\big) - 42{,}84$$

$$x = [378; 912] \rightarrow y =$$
$$= 46{,}5 \times \sin\big(0{,}00588315(x + 423)\big) - 42{,}84$$

This function is fully matched empirically and it does not reflect velocity or acceleration values. The aim of the calculations consists solely in initial and simplified modelling of the motion. More precise modelling will be the subject of further examinations. This function has been used in the further parts of this paper.

At this stage, it has been possible to calculate Reynolds number with the formula:

$$\mathrm{Re} = \frac{u \times l}{v}$$

where u is the wing tip velocity ≈ 1,72 m/s, l is the wing length ≈ 10 cm, ν is the kinematic viscosity ≈ 0,00001461 m^2/s. Thus Re ≈ 11788,9.

II.3. A 3-D Model of a Rigid Flapping Wing for CFD Simulation in FLUENT

The follow of air around butterfly wings is incompressible and the wing frequency is about 10–30 Hz [20], [21].

The governing equation is Navier-Stokes equation subject to the no-slip boundary condition [41]:

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u = \frac{\nabla p}{\rho} + \nu \nabla^2 u$$
$$\nabla u = 0$$
$$u_{bd} = u_s$$

where $u(x, t)$ is the flow field, p is the pressure, ρ is the density of the fluid, ν is the kinematic viscosity, u_{bd} is the velocity at the boundary, and u_s is the velocity of the solid.

By choosing a length scale, l, and velocity scale, u, the equation can be expressed in nondimensional form containing the Reynolds number, $\mathrm{Re} = \frac{u \cdot l}{v}$. For the dimensions of the Attacus atlas with a wingspan of 10 cm, wingtip velocity of 1.72 m/s, and air viscosity of 0.00001461 m^2/s, the Reynolds number is of Re=11,789 [39].

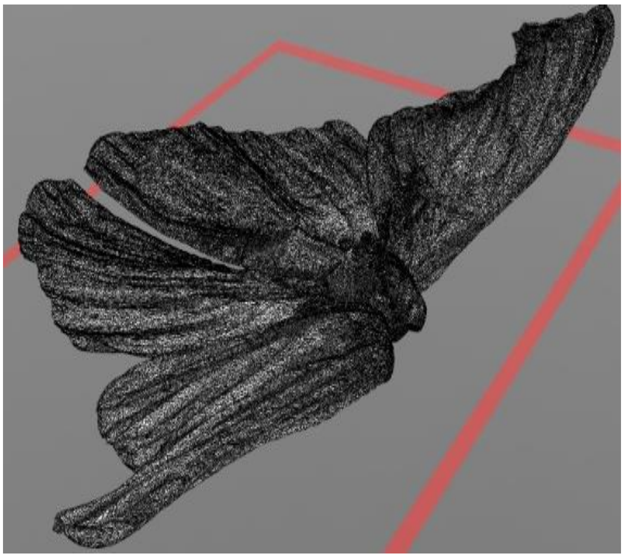


Fig. 4. Geometry obtained after scanning

A 3D model of the insect has been created for the needs of the calculations. The archetype has been a 3D scan of a real dead insect that has been simplified in the next stage in order to allow the application of the algorithms of the commercial software Ansys Fluent.

Fig. 4 presents the geometry of the insect obtained throughout scanning and repair processes. The geometry used to model the motion is presented in the next figure.

The differences between them are significant albeit necessary and, what is important, they should not cause fundamental differences in the results of the calculations.

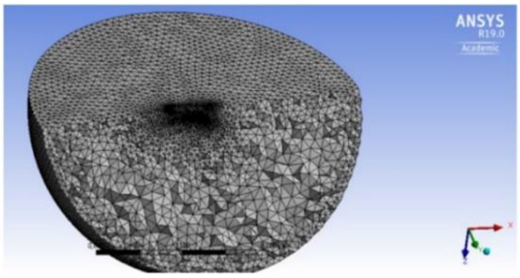
The only difference significant for the physics of fluid is the gap between the wing and the insect's body. In reality, such gap does not exist. However, currently available software does not allow conducting calculations for the cases where collisions of elements occur or one element entwines another. Hence, a measure has been a necessary.

II.4. Mesh Characteristics and Input Data

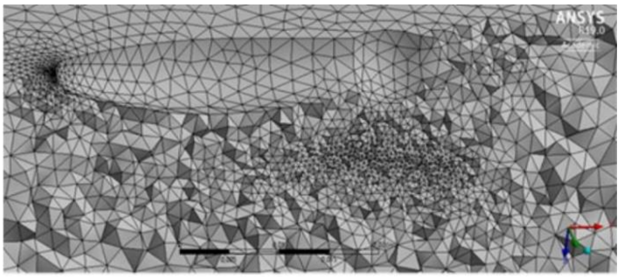
The mesh has been produced in Ansys Meshing. Tetra mesh has been used and it has been condensed at the surface of the wing, on its edges and around the rotation point by decreasing the size of the finite volume (Figs. 5). Tetra-type mesh is the best choice in the case of complex geometries or when deformations of displacement of the examined object occur. Finally, in the first sequence approximately 1.8 million elements and over 300 thousand nodes have been obtained. In the subsequent steps, the mesh has been subjected to re-meshing, which means that certain elements have disappeared while others have been created in a controlled way by the software itself.

The following boundary conditions have been set:

- symmetry;
- pressure outlet;
- wall – body;
- wall – wing.



(a)



(b)

Figs. 5. (a) Mesh in the first time step; (b) The way to refine the mesh around the key geometry elements

Symmetry coincides with the plane of insect symmetry. Pressure outlet is the outer surface of the sphere. Wall means the body of an insect and insect wing. No air intake has been defined, the same as in the real experiment. Rotation around the X-axis has been set for the wall wing. A profile file containing a series of data generated from the function mentioned above has been used. 461 time steps have been summarily generated per single stroke. One time step lasts 0.0004 second. During the selection of the turbulence model, a laminar flow model has been selected because an attempt to simulate the flow using other models would be excessively far-fetched simplification that might lead to a significant data loss [5].

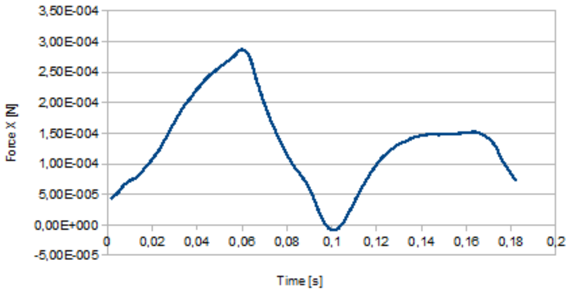
III. Results

The results have been subjected to post processing. Because the motion of a wing is a rotation around the X-axis, the values of aerodynamic forces will be different from the case of a wing rotating around three axes. Figs. 6 present graphs of the value of force affecting the wing in time, conforming to direction X, Y, and Z.

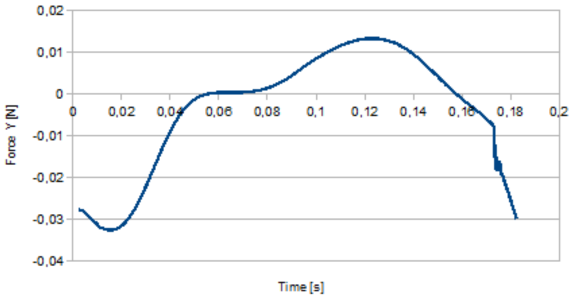
A sharp change of the function monotonicity is visible in the forces graph in Z direction in the period from 0.06 to 0.07.

This is the effect of the so-called clapping, which is the moment when the wings are in their uppermost location and change the direction of the motion. In natural conditions, the insect's wings usually collide.

This is not possible in numerical analysis because space and mesh between the wings would disappear. This is why this space is minimal during the calculation, which is sufficient for obtaining correct results. At that time the distribution of pressure is also changed, which is reflected in forces affecting the surface of the wing.



(a)



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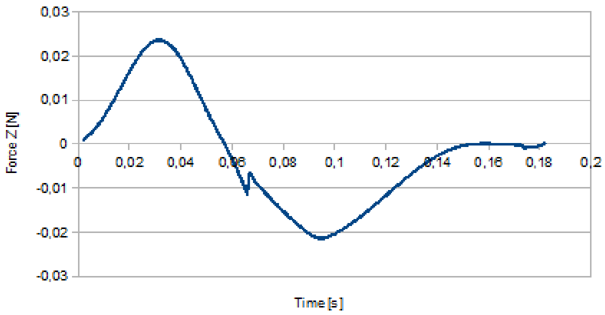


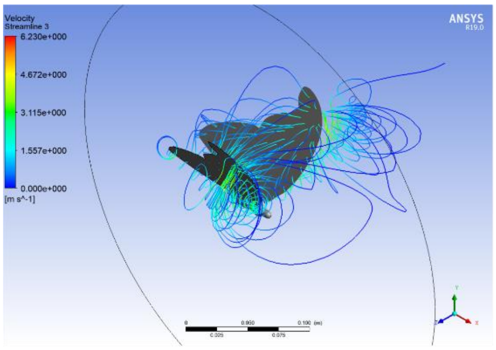
(c)

Figs. 6. Components of aerodynamic forces during one wingbeat cycle: (a) for X direction; (b) for Y direction; (c) for Z direction

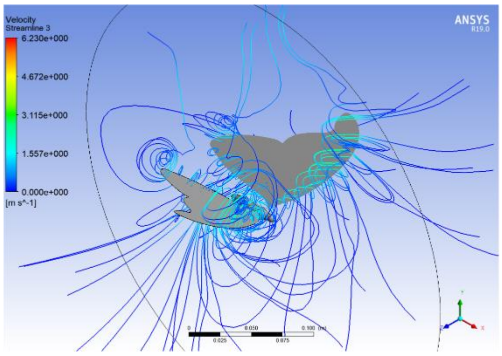
For each direction, the impulse during one stroke has been calculated. Conforming to the expectations, its value for the Y-direction does not coincide with the real movement observed for the insect, due to the stiffness of the wing. However, it is surprising that the impulse for the X-direction has a positive value (although the value is small) despite invariable attack angle. Table I shows the values of the impulse in three directions.

TABLE I
VALUES OF THE IMPULSE IN THREE DIRECTIONS

Direction	Impulse value [Ns]
X	0.00002416
Y	-0.00088061
Z	-0.00034506



(a)



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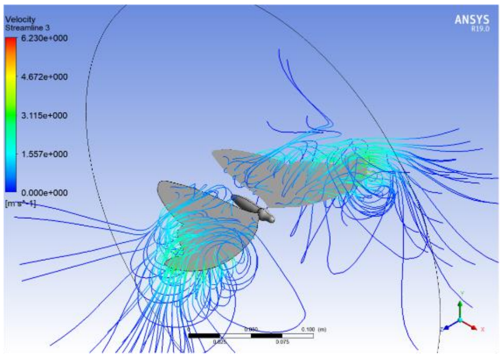


(c)

Figs. 7. Streamlines illustrating the air movement around the wing at selected times - movement from the horizontal position of the wings up and back: (a) t = 0.038 s; (b) t = 0.132 s; (c) t = 0.1824 s

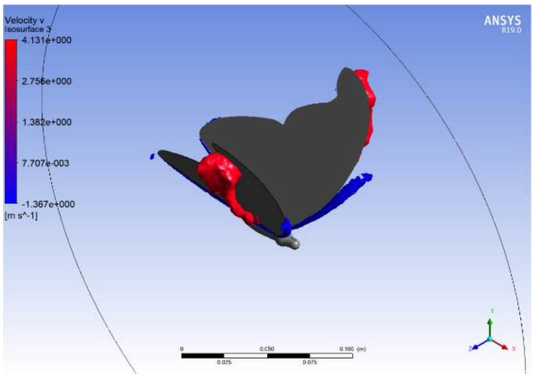
IV. Discussion

This means that the wing shape itself induces the forward flight. This conclusion can be confirmed by the system of vortex structures. Figs. 7 show the streamlines in selected wingbeats cycles. It is possible to observe vortex structures of elevated velocity at the trailing edge of the wing.

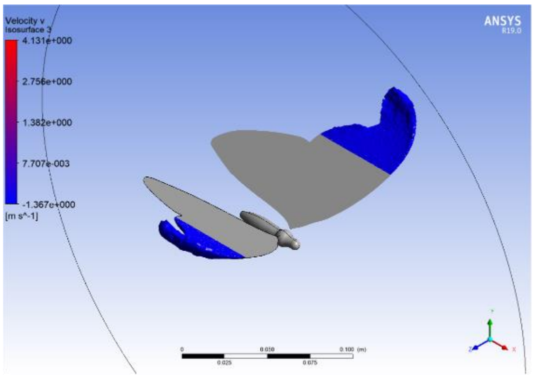
At this point, it should be noted that the space between the insect's wing and its body is created artificially for the needs of modelling. Therefore, the flow occurring there can be neglected [42].

Additionally, the pressure distributions have been generated on the wing surface. After conducting the calculations for the deformable wing motion, it will be possible to perform comparative analysis. At the present stage, it can be assumed that the greatest displacements will concern the protruding tip of the wing due to its distance from the pivot point and due to the structure.

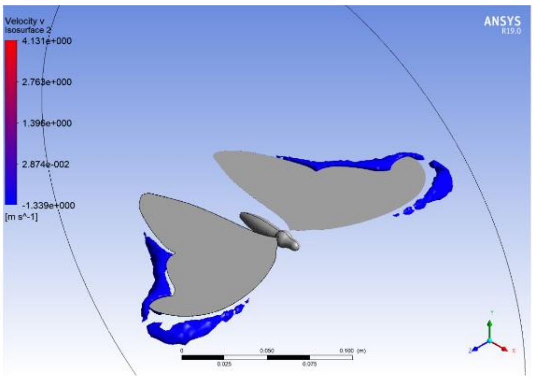
Stress concentrations directly related to the stress in the structure occur in these places. Figs. 8 show the development of vortex structures on a butterfly's wing in selected moments of the flapping cycle.



(a)



(b)



(c)

Figs. 8. Surfaces with constant velocity for the Y direction, (development of vortex structures on a butterfly's wing), at selected time moments of the flapping cycle time: (a) t = 0.038 s; (b) t = 0.132 s; (c) t = 0.1824 s

Initial analysis indicates that the distribution of pressures on an elastic wing will be characterized by lower amplitudes.

Thus, it is possible to conclude that the wing will deform in such a way as to neutralise the pressure differences over and under the lift surface. This means that current calculations will be a good point of reference in the future.

Additionally, in Figure 8(c) a residual vortex at the leading edge can be observed. Due to the stiffness of the surface, there is also a vortex on the opposite side, which nullifies the effect, but it can already be estimated that this will have an effect on increasing the lift if deformation is included.

V. Conclusion

Research and calculations described above do not exhaust the subject of the flapping flight. They are only the beginning of the deliberations, however, a very significant one. The fact that with such extensive simplifications it has been possible to show the existence of the connection between the shape of a wing and forward flight seems to be surprising. This shows that the motion of an insect is inseparably connected with its anatomy and that both these aspects require time and attention during further examinations. Only the synthesis of geometry, mechanical properties, and dynamics can allow copying this method of flight and its implication in mechanical constructions.

The scope of the research described in this article includes the numerical calculations of the rigid wing. This kind of simplification has been purposeful as it enables a preliminary description of the occurring phenomenon. In addition, in the next phase, with the use of a deformable wing, it will allow demonstrating directly the influence of material and construction data of the wing on phenomena in the field of fluid mechanics.

Fluid phenomena concerning only the rigid wing, and therefore the influence of its shape and simplified movement, are the basic axiom of butterfly movement.

The conducted study will be the starting point for considerations on the interaction of fluid and structure. The description of the flow around the rigid wing is a prelude to a complete description of the movements of deformable wings and to combine it with the mechanics of the body movement. Such a model will provide answers to construction and biological questions.

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