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Biomechanical Study of the Wing of the Dragonfly Aeshna Cyanea

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1. Introduction

The modern development of air transport enables people to travel long distances quickly and comfortably. However, the use of aircraft is expanding significantly over time. In order to access environments that are difficult for hu-mans to survive in, or extremely small, and to be able to transmit signals over a distance, the Defense Advanced Research Projects Agency (DARPA) has introduced the idea of Micro Aerial Vehicles (MAVs). Compared to con-ventional large-scale aircraft, MAVs have the great advantage of being able to hide their movement and be agile in small spaces due to their limited wingspan and weight. Such small unmanned aerial vehicle (UAV) can therefore be used for national defense and infrastructure, such as military, rescue work and ground searches in extreme environmental conditions. Early MAVs were mostly designed by downsizing conventional aircraft. However, there was a problem that such fixed-wing micro-aircraft could not hover. This led to a turn to nature. Research on the aerodynamics of insect flight was already being carried out in the 1960s (e.g. Jensen 1956). Inspired by insect biology and mechanics, scientists have developed walking, crawling and flying robots. Insect-inspired flight research has arguably been the most intensively and extensively re-searched area of all insect-related engineering research [1].

Dragonfly flight is unique. The most important flight characteristics are: speed range (lowest speed without braking, highest speed for escape and pursuit, lowest speed for long flight over a small area and highest speed for long-distance migration), endurance (more or less equivalent to power economy), acceleration (includes linear acceleration for escape and pursuit and maneuverability in various turns). These characteristics may be influenced by wing shape, size and other parameters, e.g. relatively long wings may contribute to maneuvering at high speed. Narrow wings have the further advantage that, because of their narrow-ness, the wing cores are close together, making it easier for the wing to undergo passive rotation and a greater proportion of the wing area to exert lift when the dragonfly rises [2].

An adult dragonfly can fly in six directions: up, down, forward, backward, left and right. The flight of these in-sects can generally be divided into four different modes: slow flight or hovering, forward flight (forward movement), acceleration, and free flight (gliding). The flapping wing also generates oscillations that can be used to generate lift in modes such as: fast bank, vortex catch and delayed leading edge vortex (LEV) braking [3].

The SEM can be used to investigate the structure of the wing, which can then be used to investigate its biology, aerodynamics and mechanics [4, 5]. This method also allows a very close observation of the nodes and a better understanding of how it works, leading to a better understanding of how this part of the wing deforms [6]. SEM can also be used to investigate the effect of mechanical damage to a dragonfly wing on its flight characteristics if the SEM has been preceded by a live dragonfly dynamics study.

The dragonfly wing can withstand high flapping frequencies during flight, while at the same time the wing is subject to deformation [7]. The literature indicates that the wing has a resonant frequency of more than 100 Hz and does not break if the frequency is greater than 30 Hz [8]. Other studies have shown that the flapping frequency of the dragonfly Aeshna Juncea is 27 Hz [9].

The dragonfly has the ability to control each of its wings individually, in different phases [10]. In flight, the dragonfly generates leading-edge vortices (LEVs), thus increasing its lift, and can only control the flow of air by altering the angle of attack (AoA) of the wings [11]. The primary lift contributor is the LEV, but about 35% percent of the total lift is due to rotational effects [12].

Dragonfly wings are extremely stable and can withstand comparatively high loads from gliding, hovering and flapping, even though they account for only 2% of the total mass of a dragonfly [13]. Compared to a conventional aircraft wing, a deformable wing increases lift during both wake capture and delayed stall mechanisms [14]. Computational methods have become a popular way of under-standing how biological systems work in recent decades [15]. The finite element method allows biological systems, in this case the dragonfly wing, to be studied with different parameters, which is of particular importance when studying stability in structures [16]. One example of such a dragonfly method is the numerical analysis of steady and unsteady airflow when the dragonfly is hovering. The analysis was carried out at very low Reynolds numbers and was defined by the Navier-Stokes equations. Finite element and other methods were used to facilitate the solution of these equations in computer applications [17].

The dragonfly wing membrane consists of three layers with a total thickness of about 3 μm [18]. And some veins are more elastic and flexible than others, due to the varying amount of resilin (a flexible protein found in many insects) in them [19]. Resilin is mainly found in the joints and veins, and the joints are divided into flexible and rigid according to the amount of resilin they contain [20].

This study will look at the morphological and mechanical design of the Aeshna Cyanea wing and will conduct an experiment to investigate the force generated by the dragonfly during flight. An SEM study of the dragonfly fore-wing will also be carried out to observe the veins and nodes and the wing root. In order to understand the wing vibrations, a first resonance frequency study of the forewing will be carried out.

2. Materials and methods

2.1. Specimen collection

Dragonflies are one of the best predators in the world with an outstanding 97% probability of catching its prey. The insect's flight and wings are responsible for this very good performance [21]. Like other flying insects, dragonfly wings are made of a membrane and veins. However, dragonflies are distinguished from other insects by their complex wing structure [22]. The wings of flying insects are not only for flying, but also for fighting, defense, thermoregulation, food and water collection, etc [23]. Wings often take up to 6% of a dragonfly's body mass. In some places, the thickness of the wing is less than 0.5 μm [24].

Dragonflies were captured in the summer of 2023 in southern Lithuania, in the Varėna district, near two water bodies (coordinates: 54.21550775533976, 24.292221617867497 and 54.235882399877845, 24.25285738039737). Each insect was also photographed in order to correctly identify the dragonfly species. All the described information and photographs were sent to V. Jusys, the head of the Ventės Ragas Ornithological Station, who described the dragonfly species captured. Of the 48 dragonflies captured, Aeshna Cyanea was the most abundant species, and this species was chosen for the study due to the most amount of information gathered.

Fig. 1 Dragonfly (male) Aeshna Cyanea

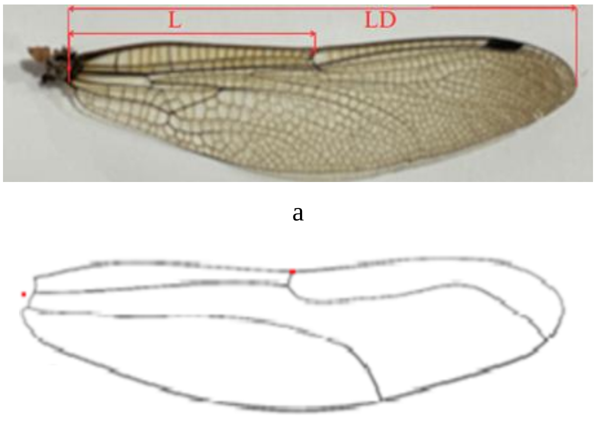
Aeshna Cyanea is a common species, evenly distributed in Lithuania. It is observed in forest sites, along rarely travelled roads, although sources say that this species is rarely found near water bodies in Lithuania, all Aeshna Cyanea dragonflies observed by the author were near water bodies [25]. The species is characterized by its large size and the blue and green coloration of its body. The average length of the body is about 75 mm and the distance be-tween the wing tips is up to 100 mm [26].

Dragonfly wings, like those of other flying insects, are made up of veins and membranes. The membrane is composed mainly of structural proteins that allow the wing to withstand high bending, twisting and aerodynamic forces during flight. As the wing rotates throughout the entire gliding cycle, it generates more lift than if the wing were not rotating during flight, in which case the membrane not only acts as a sail for the wing, but also adds stiffness to the wing [27]. The mechanical and biological properties of the wing membrane and veins, as well as the mechanical damage sustained by the wing, determine how the wing will react to the forces experienced. However, the magnitudes of the mechanical properties of the membrane vary in the literature, depending on the method of investigation and the part of the wing being investigated. For example, the Young's modulus determined by the conventional method is approximately 1 GPa, while the nano-identification method suggests 1.5 GPa. It is also possible that the mechanical properties of the membrane vary depending on the age, species, and other parameters of the dragonfly [22]. The veins of the wing are interconnected by nodes, distributed over the entire area of the wing in different shapes and sizes [14]. Nodes are divided into two groups according to their mechanical properties. In the first group (flexible nodes), the veins connect to each other over a large area, while the veins in the second group (rigid nodes) connect in such a way that they do not have any contact with each other, and the node is enriched with resilin [28]. The veins of the wing are enriched with α chitin (the most common type of chitin found in nature) and resilin, a protein that gives flexibility and elasticity to the structural parts of the wing [29].

The dragonfly species Aeshna Cyanea is very suitable for micro aerial vehicle (MAV) applications. This is because this species is widely studied by scientists. Aerodynamic studies on the wings of this species are being carried out, as well as studies on wing mechanical properties, deformations, and other parameters. Interactions between individuals of this species are also being studied and can be used for the application of biomimicry in the MAV design phase. MAV's inspired by dragonfly flight in the future may be used for military and civilian operations where it is necessary to be unseen, or to be delivered to places that are unreachable or unsurvivable by humans [30].

2.2. Wing morphology and geometry

A dragonfly wing has an extremely dense network of veins, which is made up of a few major veins emanating from the root of the wing and many smaller veins that connect the major veins. For further investigation, a photograph of the wing was imported into the software and the vein network model of the wing was reduced to simplify the model. A few main (more pronounced) veins and wing borders were left. Fig. 2, a shows a high-quality photograph of the



a

b

Fig. 2 Dragonfly Aeshna Cyanea forewing (a) and simplified geometrical model with major veins (b) forewing of Aeshna Cyanea, Fig. 2, b shows a simplified model of the forewing.

The table below shows the parameters of the dragonfly's front wing. The length and area of the wing are measured at the longest and widest point respectively, the area of the wing is calculated with the help of AutoCAD software. To simplify the calculations, it was assumed that the veins are circular in their entire length, only their outer diameter was measured, also with the help of the software. It is assumed that the diameter of the vein remains the same throughout its length. Average vein diameter was calculated by picking 5 random points of main veins in the first centimeter of the wing length, measuring the diameter of the vein in these points and calculating the average value of those diameters.

Table 1

Measured dragonfly forewing geometric parameters

Parameters	Dragonfly forewing
Width	10.58 mm
Wing vein diameter	0.11 mm
Wing area	417.85 mm²

The distance between the wing root and the nodus, marked with red dots in the Fig. 2 was also measured for further calculations, simulations, and research. As can be seen in Table 2, the distance between the root and the nodus is approximately half of the total wing length. Average distance *L* between the root and the wingtip is 43.94 mm. Calculated average distance between the root and the nodus *LD* is 21.43 mm. So, the ratio between *L* and *LD* is 0.48.

Table 2

Dragonfly wing length and distance between root and nodus

Specimen No.	Distance between the root and wingtip, *LD*	Distance between the root and nodus, *L*
1	43.43 mm	21.04 mm
2	44.02 mm	21.86 mm
3	43.12 mm	20.48 mm
4	42.48 mm	20.97 mm
5	47.31 mm	23.27 mm
6	43.27 mm	20.97 mm

In general, there has not been much research on the mechanical properties of nodus. Some literature refers to its location in the wing, other authors describe the functional characteristics of this wing structure and its influence on deformation [6, 36]. No studies could be found on the nodus as a structural element and on its degrees of freedom during flight (at different stages of flight). It is possible to think of the principle of the nodus as a human elbow or knee, but more research is needed to further investigate this wing element to see the exact structure of the nodus. In a few studies there was the ability to see a section of the nodus, but it is looks like because the amount of resilin in the nodus was tested [21].

2.3. Scanning electron microscopy

2.3.1. SEM structure

The mechanical properties of biological tissues are highly dependent on the microstructure of the tissues. In order to get to know the dragonfly of the studied species better, the forewing of Aeshna Cyanea was studied by scanning electron microscope (SEM). Monitored areas of the wing - root, nodus, vein connections, mechanic sensors. The operation of scanning electronic microscope is shown in the Fig. 3.

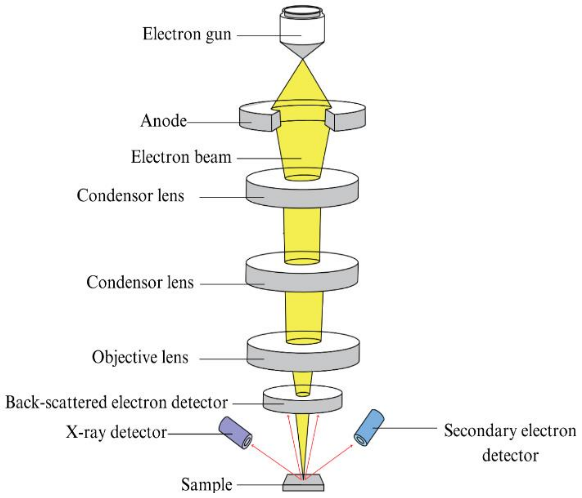


Fig. 3 Principal scheme of the SEM

After the test sample is irradiated with an electron beam in a vacuum, secondary electrons, backscattered electrons, and other signals are created. Signals from the mentioned electrons are used to reproduce images. Secondary electrons are formed near the surface of the sample, and the image obtained after detecting these electrons shows the fine structure of the sample. The SEM structure consists of a column, a chamber containing the sample, a screen, and a control section. There is a vacuum inside the column, and the released electrons from the source pass through electromagnetic lenses and become a fine beam of electrons. This electron beam is scanned longitudinally across the specimen. Meanwhile, the specimen chamber is equipped with a specimen stand with a goniometer, a secondary electron detector to detect signals emitted by the specimen, and, depending on the SEM, an electron backscatter detector and/or an X-ray detector. A vacuum pump is connected to the sample chamber to maintain vacuum in the column and chamber [31].

The dragonfly wing was examined with a tabletop SEM, which has the same principle of operation, but the micro-scope is smaller than conventional microscopes and can be placed on a table. Its dimensions are 330 mm width and 614 mm height. The microscope demonstration was carried out by “Armgate” company. The SEM used for the study was a Hitachi TM4000 series tabletop SEM. The maxi-mum magnification of this SEM is 5000. Acceleration voltages of 5 kV, 10 kV, 15 kV and 20 kV can be selected, and three choices of image types are available: secondary electron images, backscattered electron images, and a mixture of the two images. Depending on the type of sample (biological, chemical, etc.), different types of vacuum can be selected: conducting, standard and charge reducing [31].

2.3.2. Sample preparation

A dried dragonfly wing was glued to the mount with double-sided carbon tape. Next, the required height of the holder was determined and the specimen was placed in the test chamber. Later, vacuum and voltage parameters are selected. Since the specimen is biological, the vacuum type is chosen as standard and the voltage is set at 5 kV to minimize irritation of the wing surface. Fig. 4 shows the work area set up.

Computer SEM Sample

Fig. 4 Experimental stand

The study was carried out on two samples, observed from the same side of the wing. During the study, the lower zoom was used to observe a larger area of the wing, while the higher zoom was used to observe leading edge vein (a), sensors (e), vein overlaps (b, f, g), joints (c), wing root (d) and other extremely small parts of the wing structure like nodus (c).

A few photos show dust, possibly from improper storage. Preliminary dragonfly wing locations are shown in Fig. 5.

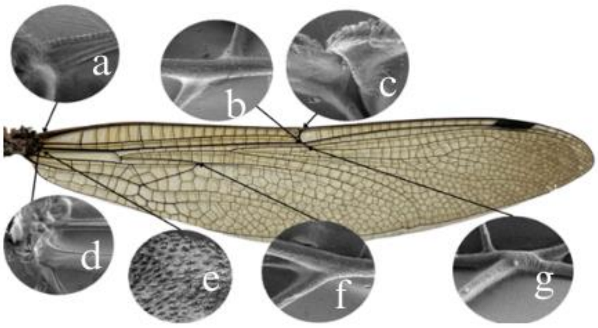


Fig. 5 SEM study areas: a – leading edge vein, b – intersection of veins, c – nodus, d – root e – mechanosensors, f – branching of the veins, g – merged veins

Fig. 6 shows the root of a dragonfly wing. It is possible to observe the irregularities of the wing, which contribute to the strength and stiffness of the wing [32]. The root of the wing is uneven due to the high concentration of veins in a small area, the connections that connect the muscles in the dragonfly's body to the wing, and the mechanic sensors that help the dragonfly read its surroundings. These sensors help monitor the condition of the wings in real time and react to changes in air flow and deformations occur-ring at the time [33].

Fig. 7 shows leading-edge vein of the forewing and a spike on it. This structure of the vein not only gives the wing excellent aerodynamic properties, but also reduces the noise level generated by the movement of the wing. The height of the visible spiked structure influences the noise attenuation property - the higher the height, the more sound is attenuated, but sound attenuation only occurs up to a certain height of the spike. The width of the spiked structure influences the distribution of pressure fluctuations in the main vein. As the width of the spikes increases, the pressure distribution moves from the front of the wing more towards the center of the wing [34].

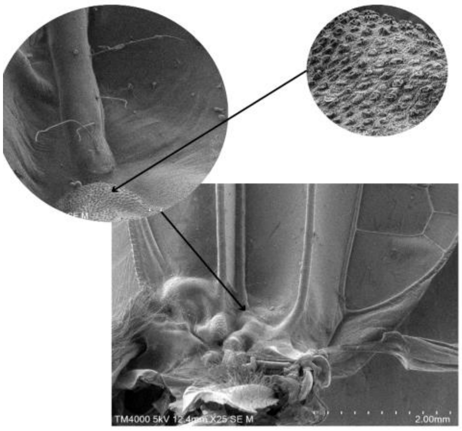


Fig. 6 Wing root

The irregularities visible in the zoomed-in view of Fig. 7 may indicate existing structural damage caused by mechanical damage, parasites, bacteria etc. This damage could also be due to the wing being stored in an unsuitable environment, so that the wing may have been exposed to dust and moisture. At the wing root, the veins and membrane are thicker compared to the wing tip, providing stability under both inertial and aerodynamic loads. The costal veins change shape along the entire length of the wing, i.e. It is not circular. These shapes help the wing to withstand the loads created in that area of the wing. In the part of the wing to be deformed, the cross-veins are covered with a membrane strip which helps the cross-vein to rotate slightly when the longitudinal vein rotates [35].

Fig. 8 shows the costal, subcostal, and radial veins connecting the nodus (a) in the center of the wing. This nodus is elastic and flexible, allowing the wing to bend through its center in flight. Other veins (b, c) are staying in their degrees of freedom and the veins entering the node have more degrees of freedom. The main purpose of this node is to

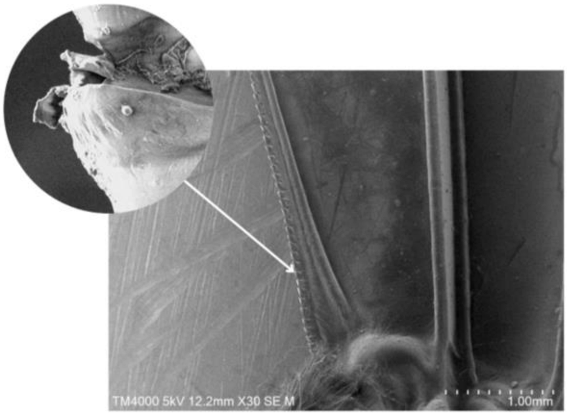


Fig. 7 Leading edge vein of a forewing

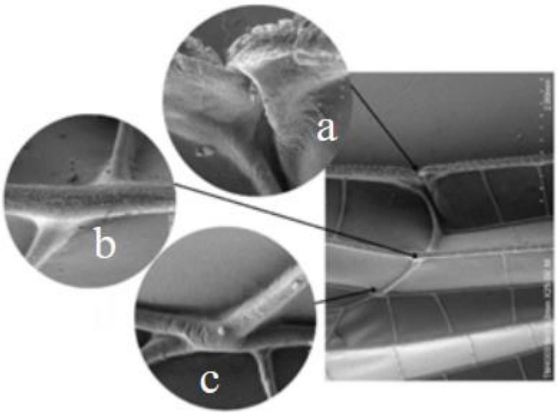


Fig. 8 Nodus and veins of a forewing: a – nodus, b – interseption of veins, c – merged veins

reduce the received loads [36].

SEM studies can be extremely useful in the development of micro aerial vehicles, by biomimicking a dragonfly wing it is possible to design small drones that are inspired by the best flight of the world's predator.

2.4. Dragonfly wing dynamic analysis

2.4.1. Test work area

The vibrations of a dragonfly's forewing have been studied. An attempt was made to find the first resonant frequency of the wing of Aeshna Cyanea by means of a "bump" test and a forced excitation test. Both tests were both carried out on the same work stand, the structure of which can be seen in the Fig. 9.

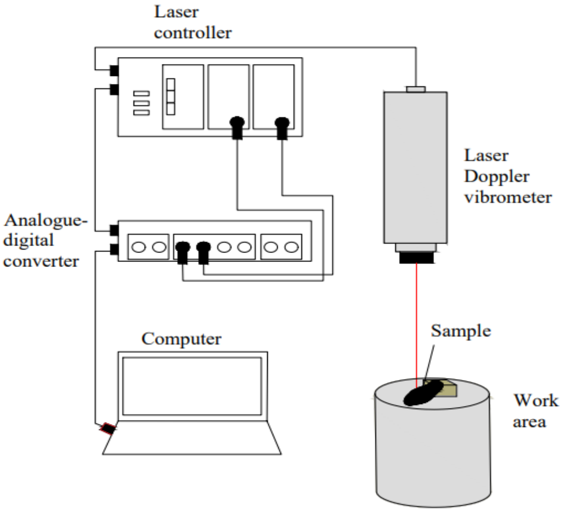


Fig. 9 „Bump" test and forced excitation test principal scheme, computer shows "Pico-Scope 6" software

2.4.2. Specimen preparation

The mass of a dragonfly wing is approximately evenly distributed over the entire wing area, so that this value can be considered constant, whereas the wing stiffness starts to change when contact with air occurs, since air has a drag as well as a compressibility. So, when the amplitude of vibration increases, the wing is actually moving more in the air, so the air has a greater influence on the wing – fluid/structure phenomena.

The root of the wing was glued to a wooden block, which was attached to a Doppler vibrometer that was connected to a Polytec OFV-5000 controller. The challenge in this study was to find a suitable point on the wing where the laser beam did not pass through (the most accurate results were obtained by applying the laser beam to a prominent vein at the end of the wing). The wing vibration data from the study was read in PicoScope 6.

Laser beam was directed to a specific point of the wing tip, that is shown in the Fig. 10.

Fig. 10 Point (red mark) on the wing that laser was directed to

This point was chosen because of the thinness of the wing tip, the laser beam could easily pass through the membrane, so vein was chosen instead.

2.4.3. Results

The "bump" test was carried out on two Aeshna Cyanea forewings and the results are presented in Fig. 11, Fig. 12, Fig. 13 and Fig. 14.

From the available graphs it is possible to observe how the wing stops oscillating after only a few oscillations after hitting the work bench (the highest jump in the graph). For the first wing "bump" test, the oscillations stop at about 60 ms and the frequency between the two peaks T=12.26 ms. With this value it is therefore possible to determine the first resonant frequency with Eq. 1:

$$f = \frac{1}{T} = 81.56 \text{ Hz}. \tag{1}$$

Here: T is period, s, f is frequency, Hz.

As can be seen from the results of the "bump" test for the second wing, more oscillations occur before settling compared to the first wing. The time between peaks was found to be 9.8 ms. Using the above calculations, the first resonant frequency of the second wing was determined to be 101,75 Hz.

From the results of the "bump" test, further investigations can be carried out to investigate the damping of the wing in contact with the air and to further investigate the application of this dragonfly species to MAV's. The "bump" test was carried out to see if it is even possible to find the first resonant frequency of the wing with such a small bioassay.

The same parameter was further investigated, but by a different method, by setting a certain steady vibration frequency of the work bench (shown in red in the graphs) and observing the wing vibrating (shown in blue in the graphs). The result of the first wing test with forced excitation is shown in Fig. 13.

As can be seen from the graphs, the highest point reached by the blue curve was at 88.4 mV and the period was set at 12.71 ms. Compared to the "bump" test result, the difference is only 0.45 ms, which corresponds to 2.2 Hz after the calculation.

The results of the second wing test were also similar for both test methods. The period of oscillation was found to be 10.4 ms, a difference of 0.572 ms compared to the first wing tested by the first method, corresponding to 1.74 Hz. The highest point of the curve was found at 64.23 mV. The results of second dragonfly's forewing forced excitation test is shown in Fig. 14. The first and second specimen resonant frequencies are so different because the first specimen area is bigger than the second specimen area.

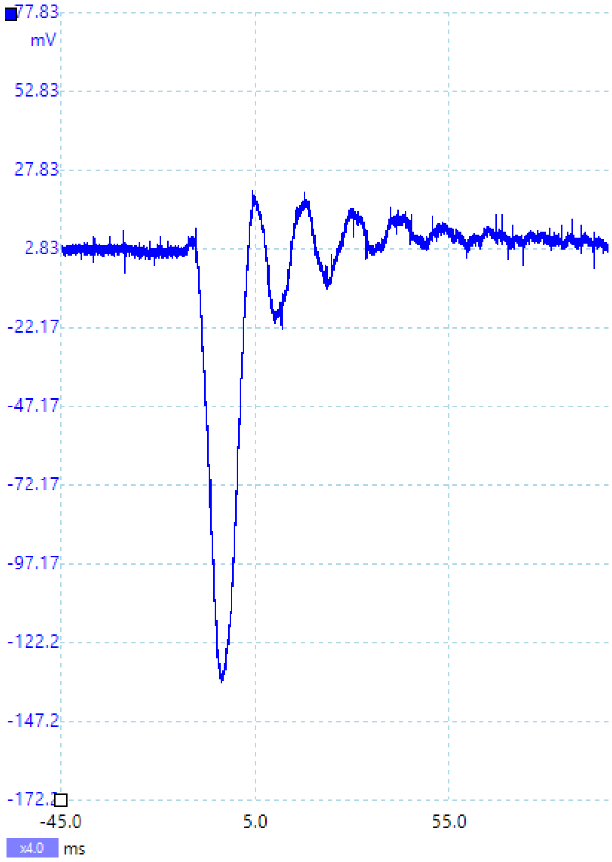


Fig. 11 „Bump“ test results of the first specimen

3. Discussion

This study investigated the basic characteristics of the dragonfly wing, which will be further investigated in future studies. The study involved the wings of real Aeshna Cyanea dragonflies, which were dried in a room environment and subsequently subjected to SEM and vibration studies.

The Aeshna Cyanea dragonfly was chosen because it was the species with the highest capture rate and it was judged that studying a single species of dragonfly would

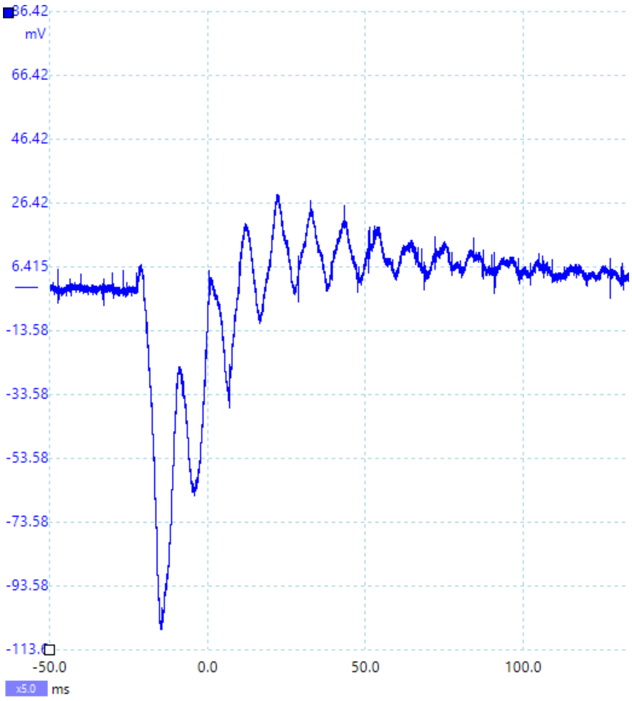


Fig. 12 „Bump“ test results of the second specimen

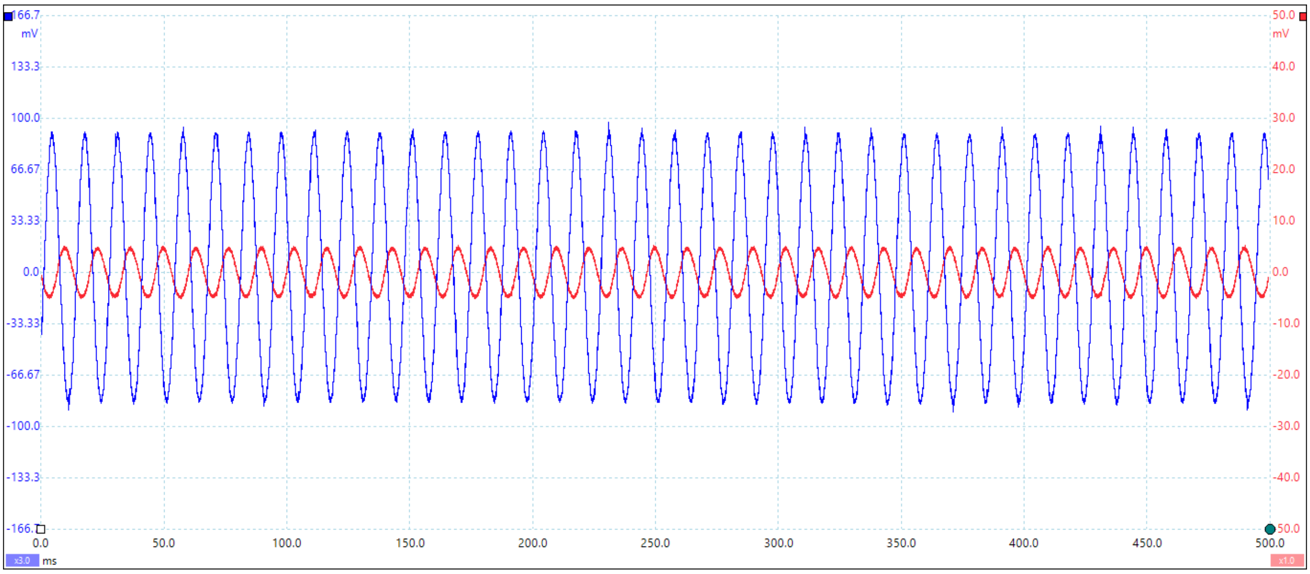


Fig. 13 Kinematic excitation on the first wing specimen: red - vibration of the vibrometer, blue - vibration of the wing

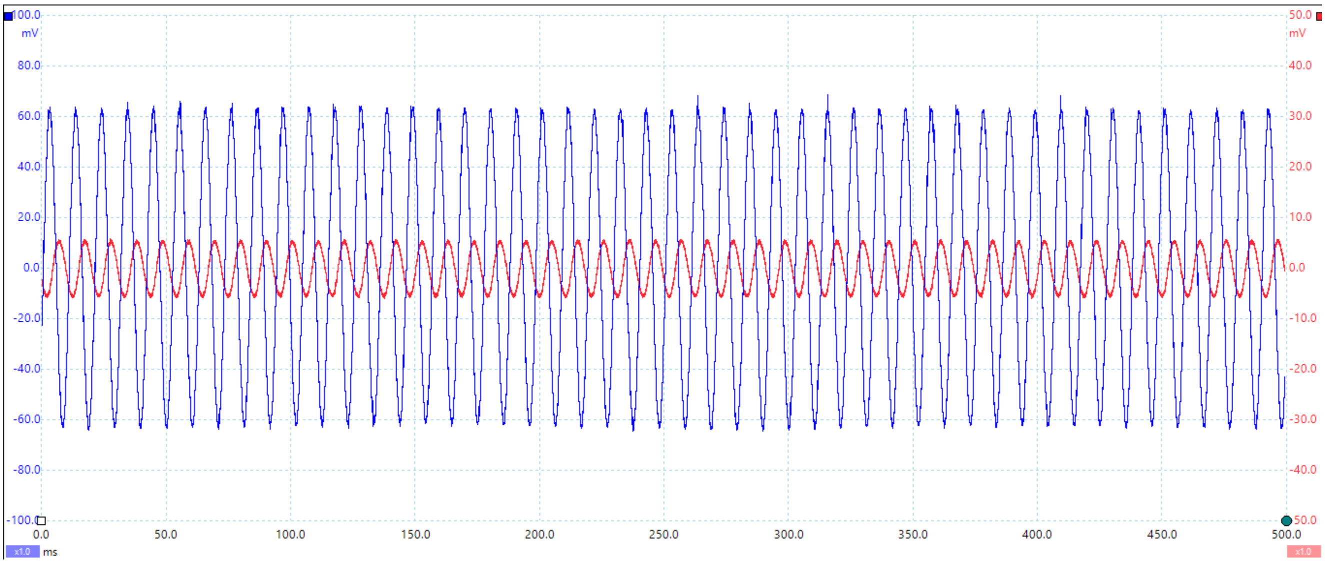


Fig 14 Kinematic excitation on the second wing specimen: red - vibration of the vibrometer, and blue - vibration of the wing

provide the most accurate results. This dragonfly species is not often used for surveys, with Aeshnidea dragonflies being more commonly surveyed than Aeshna Juncea dragonflies, probably due to the higher prevalence of this species in the countries where surveys are carried out.

The morphology of the dragonfly is so peculiar that it has remained virtually unchanged since the appearance of this insect. The veins and joints in dragonfly wings contain the protein resilin, which gives the wing its flexibility and elasticity. Many different studies have been carried out on the morphology of the wing (SEM, TEM, etc.), but few researchers have studied the wing's nodus, its morphology and its mechanics, although this part of the wing contributes to the wing's flexibility and absorbs a very large amount of incoming loads during flight.

The scanning electron microscope study on Aeshna Cyanea forewing gives us good understanding of morphology and structure, and how the wing looks like from microscopic level. This research method opens up new possibilities for MAV modelling and mimicry of the wing. Various studies have shown how mechanical damage to the wing affects the flight, how the wing vein section looks like at different locations etc.

The studies on the dragonfly's wing dynamics can give a very good understanding of how the wing itself works. From the biomimicry point of view the studies on the wing dynamics can help with designing and modelling of the artificial wing of the MAV. Both wing vibration tests have shown that the wing vibration can be investigated by different methods and the results will be the same. However, the results obtained cannot be considered as a general feature of the species, as the amplitude of the wing vibration also depends on the wing area, the influence of the air on the compressibility and other parameters.

4. Conclusions

1. Over the last few decades, a lot of research has been carried out on dragonflies to understand their morphology and mechanics, with a view to applying this to the development of MAVs. A review of the literature has provided an overview of wing biological properties, resilin, wing morphology and mechanical characteristics. The dragonfly Aeshna Cyanea, which is one of the most common dragonflies of the family Aeshnidea in Lithuania, was studied in this study.

2. Dragonflies were captured for the study and their geometrical characteristics such as mass, wing spacing, and body length were examined to identify the species. Forewing geometric parameters were measured. The location of the nodus on the wing was measured. Average distance between the wing root and the wingtip from the 6 measured forewings was 43.94 mm. Calculated average distance between the root and the nodus was 21,43 mm. The ratio between the average wing length and the distance between the root and the nodus is 0.48.

3. The study also included an SEM study of the dragonfly forewing, which provided an overview of the wing structure and an insight into the different structural parts and their characteristics in relation to the overall wing. Several areas were observed during the study: root, overlapping veins, leading-edge vein, nodus.

4. Also, investigations were carried out to find the first resonant frequency of the wing. It was observed from the tests that both the bump test and the forced excitation test gave very similar results. The first resonant frequency of the first wing was found to be 81.56 Hz and that of the second wing tested was 101.75 Hz. Future research will further investigate the mechanics of dragonfly wings, dragonfly dynamics and its application to MAV's.

References

1. **Chen, L.; Zhang, Y.; Zhou, C.; Wu, J.** 2019. Aerodynamic mechanisms in bio-inspired micro air vehicles: a review in the light of novel compound layouts, IET Cyber-Systems and Robotics 1(1): 2–12. https//doi.org/10.1049/iet-csr.2018.0007.
2. **Wootton, R.** 2020. Dragonfly flight: morphology, performance and behavior, International Journal of Odonatology 23(1): 31-39. https://doi.org/10.1080/13887890.2019.1687991.
3. **Salami, E.; Ward, T.A.; Montazer, E.; Ghazali, N.N.N.** 2019. A review of aerodynamic studies on drag-

onfly flight, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 233(18): 6519-6537.
https://doi.org/10.1177/0954406219861133.

4. **Darvizeh, M.; Darvizeh, A.; Rajabi, H.; Rezaei, A.** 2009. Free vibration analysis of dragonfly wings using finite element method, The International Journal of Multiphysics 3(1): 101-110.
https://doi.org/10.1260/175095409787924454.
5. **Zhang, S.; Sunami, Y.; Hashimoto, H.** 2018. Deformation behavior of dragonfly-inspired nodus structured wing in gliding flight through experimental visualization approach, Scientific Reports 8: 5751.
https://doi.org/10.1038/s41598-018-24237-x.
6. **Rajabi, H.; Ghoroubi, N.; Stamm, K.; Appel, E.; Gorb, S.N**. 2017. Dragonfly wing nodus: A one-way hinge contributing to the asymmetric wing deformation, Acta Biomaterialia 60: 330-338.
https://doi.org/10.1016/j.actbio.2017.07.034.
7. **Naka, H.; Hashimoto, H.** 2015. Effects of deformation and vibration characteristics of wings on flapping flight, Mechanical Engineering Journal 2(1): 14-00262.
https://doi.org/10.1299/mej.14-00262.
8. **Chen, J.S.; Chen, J.Y.; Chou, Y.F.** 2008. On the natural frequencies and mode shapes of dragonfly wings, Journal of Sound and Vibration 313(3-5): 643–654.
https://doi.org/10.1016/j.jsv.2007.11.056.
9. **Norberg, R.Å.** 1975. Hovering Flight of the Dragonfly Aeschna Juncea L., Kinematics and Aerodynamics. In: Wu, T.YT., Brokaw, C.J., Brennen, C. (eds) Swimming and Flying in Nature. Springer, Boston, MA.
https://doi.org/10.1007/978-1-4757-1326-8_19.
10. **Peng, L.; Pan, T.; Zheng, M.; Song, S.; Su, G.; Li, Q.** 2022. Kinematics and Aerodynamics of Dragonflies (Pantala flavescens, Libellulidae) in Climbing Flight, Frontiers in Bioengineering and Biotechnology 10: 795063.
https://doi.org/10.3389/fbioe.2022.795063.
11. **Wang, J. K.; Sun, M.** 2005. A computational study of the aerodynamics and forewing-hindwing interaction of a model dragonfly in forward flight, Journal of Experimental Biology 208(19): 3785–3804.
https://doi.org/10.1242/jeb.01852.
12. **Salami, E.; Montazer, E.; Ward, T. A.; Ghazali, N. N. N.; Badruddin, I. A.** 2022. Aerodynamic Performance of a Dragonfly-Inspired Tandem Wing System for a Biomimetic Micro Air Vehicle, Frontiers in Bioengineering and Biotechnology 10: 787220.
https://doi.org/10.3389/fbioe.2022.787220.
13. **Sun, J.; Ling, M.; Pan, C.; Chen, D.; Tong, J.; Li, X.** 2014. BIOMIMETIC STRUCTURE DESIGN OF DRAGONFLY WING VENATION USING TOPOLOGY OPTIMIZATION METHOD, Journal of Mechanics in Medicine and Biology 14(4): 1450078.
https://doi.org/10.1142/S021951941450078X.
14. **Du, G. Sun, M.** 2010. Effects of wing deformation on aerodynamic forces in hovering hoverflies, Journal of Experimental Biology 213(13): 2273-2283.
https://doi.org/10.1242/jeb.040295.
15. **Wootton, R. J.; Herbert, R. C.; Young, P. G.; Evans, K. E.** 2003. Approaches to the structural modelling of insect wings, Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 358(1437): 1577–1587.
https://doi.org/10.1098/rstb.2003.1351
10.1098/rstb.2003.1351.
16. **Kesel, A. B.; Philippi, U.; Nachtigall, W.** 1998. Biomechanical aspects of the insect wing: an analysis using the finite element method, Computers in biology and medicine 28(4): 423-437.
https://doi.org/10.1016/S0010-4825(98)00018-3.
17. **Mehdi, H.; Lakhera, B. K.; Kamboj, A.** 2014. Numerical Analysis of Steady and Unsteady Flow for Dragonfly Wing Section in Gliding Mode, International Journal of Advanced Mechanical Engineering 4(4): 365-370.
18. **Xiao, K.; Bai, K.; Wang, W.; Song, F.** 2007. Experimental study on the microstructure and nanomechanical properties of the wing membrane of dragonfly, Acta Mechanica Sinica 23(3): 281–285.
https://doi.org/10.1007/s10409-007-0070-9.
19. **Donoughe, S.; Crall, J. D.; Merz, R. A.; Combes, S. A**. 2011. Resilin in dragonfly and damselfly wings and its implications for wing flexibility, Journal of Morphology 272(12): 1409–1421.
https://doi.org/10.1002/jmor.10992.
20. **Hou, D.; Zhong, Z.; Yin, Y.; Pan, Y.; Zhao, H.** 2017. The Role of Soft Vein Joints in Dragonfly Flight, Journal of Bionic Engineering 14(4): 738-745.
https://doi.org/10.1016/S1672-6529(16)60439-0.
21. **Rajabi, H.; Gorb, S.N.** 2020. How do dragonfly wings work? A brief guide to functional roles of wing structural components, International Journal of Odonatology 23(1): 23-30.
https://doi.org/10.1080/13887890.2019.1677515.
22. **Córdoba-Aguilar, A.; Beatty, C.; Bried, J.** 2023. Dragonflies and Damselflies: Model Organisms for Ecological and Evolutionary Research, 2 Ed. Oxford: Oxford University Press. 459p.
https://doi.org/10.1093/oso/9780192898623.001.0001.
23. **Rudolf, J.; Wang, L.-Y.; Gorb, S.N.; Rajabi, H**. 2019. On the fracture resistance of dragonfly wings, Journal of the Mechanical Behavior of Biomedical Materials 99: 127–133.
https://doi.org/10.1016/j.jmbbm.2019.07.009.
24. **Robin, J. W.** 1992. Functional Morphology of Insect Wings, Annual Review of Entomology 37: 113-140.
https://doi.org/10.1146/annurev.en.37.010192.000553.
25. **Gliwa, B.; Švitra, G.; Petraška, A.; Uselis, V.; Jusys, V.** 2019. Lietuvos laumžirgių paplitimo atlasas (Distribution atlas of dragonflies of Lithuania). Kruenta. 120 p. (in Lithuanian).
26. **Gliwa, B.; Švitra, G.** 2016. Lietuvos laumžirgiai (Odonata of Lithuania). Kruenta. 354p. (in Lithuanian).
27. **Combes, S. A.; Daniel, T. L.** 2003 Flexural stiffness in insect wings I. Scaling and the influence of wing venation, Journal of Experimental Biology 206(17): 2979-2987.
https://doi.org/10.1242/jeb.00523.
28. **Rajabi, H.; Stamm, K.; Appel, E.; Gorb, S.N.** 2018. Micro-morphological adaptations of the wing nodus to flight behaviour in four dragonfly species from the family Libellulidae (Odonata: Anisoptera), Arthropod Structure & Development 47(4): 442-448.
https://doi.org/10.1016/j.asd.2018.01.003.
29. **Wei, A.; Fu, J.; Guo, F.** 2021. Mechanical properties of chitin polymorphs: A computational study, Journal of Materials Science 56(20): 12048–12058.
https://doi.org/10.1007/s10853-021-06086-8.

30. **Srigrarom, S. Thipyopas, C.** 2015. Aerodynamics of Southern Hawker Dragonfly: Aeshna cyanea, 33rd AIAA Applied Aerodynamics Conference. Published by the American Institute of Aeronautics and Astronautics, Inc.
https://doi.org/10.2514/6.2015-3156.
31. Let’s Familiarize Ourselves with the SEM. Hitachi High-Technologies Corporation.
32. **Jongerius, S. R.; Lentink, D**. 2010. Structural Analysis of a Dragonfly Wing, Experimental Mechanics 50(9): 1323–1334.
https://doi.org/10.1007/s11340-010-9411-x.
33. **Fabian, J.; Siwanowicz, I.; Uhrhan, M.; Maeda, M.; Bomphrey, R. J.; Lin, H.-T.** 2022. Systematic characterization of wing mechanosensors that monitor airflow and wing deformations, iScience 25(4): 104150.
https://doi.org/10.1016/j.isci.2022.104150.
34. **Jiang, S.; Hu, Y.; Li, Q.; Wang, H.; Lin, Y.; Zhou, X.; Liu, Q.** 2021.The Noise-Reduction Characteristics of Microstructure of Dragonfly Wing Leading Vein, Applied Sciences 11(7): 2970.
https://doi.org/10.3390/app11072970.
35. **Bechert, D.; Meyer, R.; Hage, W.** 2000. Drag reduction of airfoils with miniflaps - Can we learn from dragonflies?, AIAA 2000-2315. Fluids 2000 Conference and Exhibit.
https://doi.org/10.2514/6.2000-2315.
36. **Sun, J.; Bhushan, B.** 2012. The structure and mechanical properties of dragonfly wings and their role on flyability, Comptes Rendus Mécanique 340(1–2): 3-17.
https://doi.org/10.1016/j.crme.2011.11.003.

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BIOMECHANICAL STUDY OF THE WING OF THE DRAGONFLY AESHNA CYANEA

Summary

Aeshna Cyanea is a species of dragonfly in the Aesnidea family. In this study, morphology and mechanical proper-ties of dragonfly were investigated. The location of the nodus on the wing was observed. A SEM study was also carried out to get a closer look at the mechanical structure of the dragonfly wing. A dynamic study of the wing was carried out to and the first resonant frequency of the wing was found. Future research will cover dragonfly wing mathematical model and simulation of the wing dynam-ics.

Keywords: dragonfly Aeshna Cyanea, SEM, resonance vibration, morphology, forewing.

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