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EXPERIMENTAL STUDIES OF THE FLAPPING MOTION OF A BUTTERFLY WING MODEL

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The article describes an experiment of the movement of a butterfly wing model in glycerin to obtain a relationship between rotation functions and aerodynamic forces. Measurements were taken during the movement of an artificial wing, modelled on a real one, in a dense viscous medium with proportional reduction of the movement frequency. Reducing the frequency, i.e. slowing down the wing, makes the observation easier and produces more reliable results. The tests started with the movement observed in the living butterfly and then, in each subsequent step, the angles of inclination were modified in such a way as to describe it in terms of simple functions, without losing their physical properties, i.e. due to aerodynamic forces. According to the literature, the insect flight can be divided into three phases of stroke in flapping flight. In each, aerodynamic forces are generated or aerodynamic drag is minimised. The experimental tests were filmed, and the pressure differences were measured. Based on the data analysis, the functions of wing inclination angles in time for the characteristic flight moments – acceleration, hover, and take-off – were specified.

Keywords: flapping flight, butterfly flight, experimental mechanics, verification of numerical calculations

1. Introduction

In literature, the flight of living organisms is often discussed, but there appears a varied phenomenon making its individual aspects still not well understood (Shyy *et al.*, 2007). The aim of this article is to understand deformations of a butterfly wing and their impact on aerodynamic forces. One of the first significant publications that attempted to explain the key issues related to aerodynamics of flapping insect wings was a series of six articles by Ellington (1984). The article (Reade and Jankauski, 2020) 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). The description did not cover wing deformations or insect in-flight position, as in most studies. Fry *et al.* (2005) present insect flight research results (on the example of a Drosophila Melanogaster fruit fly). The authors distinguish three flapping wing motion phases – beat, break-off and rotation, while noting that the wing motion in each insect is a species feature. The article (Steppan, 2000) presents a series of studies of displacements as well as forces and torques acting on the wings of Idea leuconoe butterfly in flapping flight. The analysis discussed in (Piechna, 1997) indicates that the lift force in a fly is generated mainly in the course of downwards wing motion, and the thrust during upwards wing motion. 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 that moment. This produces an increase in thrust by up to 40%. It should be noted that butterflies are classified as insects with a low beat frequency, large area and span of the wings (Sun and Bhushan, 2012). Based on the analysis of source literature data, the authors of (Sun and Bhushan, 2012) state that a butterfly flying forwards always flaps, while combining flapping with gliding to improve flight efficiency. Experimental studies of vortex structures generated by the wings of a Papilio Ulysses were also reviewed in (Hu *et al.*, 2009). The authors of (Okamoto *et al.*, 2009; Hu and Wang, 2010) discuss the gliding flight. Senda *et al.* (2012) calculate the aerodynamic force by applying a model composed of numerous rigid elements, and compare the results with a force measured in the course of the experiment. A two-dimensional analysis of flexible wing flow is presented in (Bluman and Kang, 2017), where the authors attempt to show that wing flexibility leads to an increase in its lift force. Biej-Bijenko (1976) considers 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. Essentially, the information required for this work is that the 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) (Ha *et al.*, 2011).

In order for the research described in this article to be carried out, the investigation and calculations constituting the introduction herein were previously performed: Numerical calculations of the flow around the rigid wing have been carried out, which was necessary (Kunicka-Kowalska *et al.*, 2022b) to start the research. Then, by increasingly complicating the modelling, the model became more realistic by taking into account the flexibility of the wing structure (Kunicka-Kowalska and Sibilski, 2018; Kunicka-Kowalska *et al.*, 2022a). The mechanical properties of this butterfly wings were studied in (Landowski *et al.*, 2010) and taken from the literature (Sun and Bhushan, 2012). The input data for calculations were obtained from an experiment with a live Attacus Atlas insect (Kunicka-Kowalska and Sibilski, 2018). Numerical calculations were performed in the commercial Ansys Fluent software, the algorithms of which are based on the Navier-Stokes equation. In order to validate the deformation and experimentally demonstrate the influence of the modification of the wing rotation on pressure differences of the medium resulting in aerodynamic forces, the tests described in this article were carried out.

2. Materials and methods

Because the frequency of flapping in the air is high and makes experimental work and observation impossible, it was decided to use technical glycerin as the medium. It is a thick and colourless liquid. It was assumed that deformations are caused by propulsive forces of the medium in which the object is moving, so to obtain the same deformations, these forces had to be compared.

$$\varepsilon_p = \varepsilon_g - F_{rp} = F_{rg} \tag{2.1}$$

where: ε_p – deformation in the air, ε_g – deformation in the glycerin, F_{rp} – resistance force in the air, F_{rg} – resistance force in the glycerin.

Following the above reasoning, the frequency that would give analogous deformations was determined by the formula

$$C\frac{\rho_p v_p^2}{2}S = C\frac{\rho_g v_g^2}{2}S \tag{2.2}$$

where: ρ_p – air density, ρ_g – glycerin density, v_p – object velocity in the air, v_g – object velocity in the glycerin, S – area of projected object on a plane perpendicular to the velocity vector.

Since in both cases the object is the same and the frequency is directly proportional to the velocity, the equation can be reduced to a simple proportion

$$\frac{v_g}{v_p} = \sqrt{\frac{\rho_p}{\rho_g}} = \frac{f_g}{f_p} \quad \rightarrow \quad f_g = \sqrt{\frac{\rho_p}{\rho_g}} f_p \quad \rightarrow \quad f_g = \sqrt{\frac{0.00119}{1.26}} 5.48 = 0.168 \text{ Hz} \tag{2.3}$$

where: f_p – frequency in the air, f_g – frequency in the glycerin.

Based on previous research (Kunicka-Kowalska *et al.*, 2022b), the flutter frequency was set to 5.48 Hz. This means that in one minute, the wing will beat 10.08 times, and one stroke will take about 5.95 s. This is a speed suitable for observing deformations, so glycerin is the right medium for this experiment. It can also be easily concluded that with the application of water, this speed would be higher

$$\frac{v_w}{v_p} = \sqrt{\frac{\rho_p}{\rho_w}} = \frac{f_w}{f_p} \quad \rightarrow \quad f_w = \sqrt{\frac{\rho_p}{\rho_g}} f_p \quad \rightarrow \quad f_g = \sqrt{\frac{0.00119}{1}} 5.48 = 0.189 \text{ Hz} \tag{2.4}$$

where: f_w – frequency in water.

Thus, it can be seen that in one minute, the wing will perform 11.34 strokes in water while maintaining the same deformations. However, the Reynolds number, which depends on the fluid viscosity and the remaining dimensionless numbers, was also important for the experiment. Table 1 shows the dimensionless numbers for the flapping wing in water and glycerin while maintaining the deformations observed in the air. The biggest difference is in the Reynolds number. The use of glycerin instead of water allows for any orientation of the wing in space and easier interpretation of the pressure reading in the liquid, which indicates the initial direction and returns of the fluid velocity vector at the wing surface. The authors of the article [19] demonstrate the relationship between the Strouhal number and aerodynamic forces in a flapping flight. In the case in question, however, the movement lasts a short time: the pressure is measured during one stroke. In this situation and with high fluid viscosity, which in turn significantly affects the Reynolds number, the fluid dynamics is reduced and, consequently, the velocity has a limit at zero. This means that regardless of the time instant, the dimensionless Strouhal number will tend to infinity. This allows for a qualitative comparison of pressures and a quantitative comparison of deformations as a simplification to solid mechanics. Table 1 contains dimensionless numbers for continuous motion at the same wing speed.

Table 1. Dimensionless number for the flapping wing in water and glycerin while maintaining the deformations observed in the air

Dimensionless number	Value in water	Value in glycerine
Reynolds number, Re	6.6715	0.0057
Non-dimensional frequency, k	1.0000	1.0000
Strouhal number, St	0.5000	0.5000

To obtain deformations similar to those in nature and to correctly conduct the experiment, it was necessary to choose the right material. The most important properties of the material sought were:

- high flexibility,
- no or negligible hygroscopicity – constant parameters after immersion in glycerin,
- isotropy (different flexibility is to be obtained by varying the thickness of the model),
- ease of processing and forming.

It was decided that the best solution would be to use silicone. Young's modulus of moulding silicone is 0.0015 GPa. From the formula for theoretical Young's modulus, the thickness that should be kept so the elasticity constant E_c does not change was calculated (Kunicka-Kowalska,, 2020). The model was made in two stages: the veins system and membrane. First, a container was prepared and raised on one side to a given height. There is a fluid level mark in the container. Blue moulding silicone was poured into the prepared container. Thanks to the prepared form, a variable thickness of the initial element was obtained. After concentration, the silicone was deformed, a vein template was applied (Kunicka-Kowalska *et al.*, 2022a) and the lines were cut manually. Next, the container was prepared again (this time by setting it horizontally), and a line pattern was placed on the bottom. A thin layer of transparent moulding silicone was then poured over it. After obtaining a uniform thickness of the layer, the blue trough was arranged according to the diagram at the bottom of the container. After binding, the whole was deformed, and the wing was cut along the contour, applying the template again. Through this procedure, a uniform material was obtained (with the same properties), with no gluing, which made it possible to avoid the additional stiffness of the adhesive. In addition, the veining is highlighted in blue. The wing membrane remained transparent allowing the phenomena to be seen on the other side of the wing surface. Therefore, it was possible to create a real model characterized by the same susceptibility to deformation as the real wing. Additionally, the model made it possible to observe the phenomena in front and behind it due to its transparency. The difference between the real wing and the model was visible in the thickness of the element, which was a necessary simplification to obtain the same deformations. The wing was seated with a sleeve, with the mount in the air, not in the liquid. It was not possible to fully immerse the arm because the servomotors could not be submerged – their sealing would be insufficient under the high pressure of the column of a thick liquid (real model see Fig. 1).

Fig. 1. Photo of the actual model

The next step was to model the changes in inclination angles of the artificial wing. The wing kinematics is described in the control program as rotations around the axis: roll around axis X, yaw around axis Y, pitch around axis Z (see Fig. 2). To realize the movement physically as rotation around axes passing through one point, three servomotors were used. Each is responsible

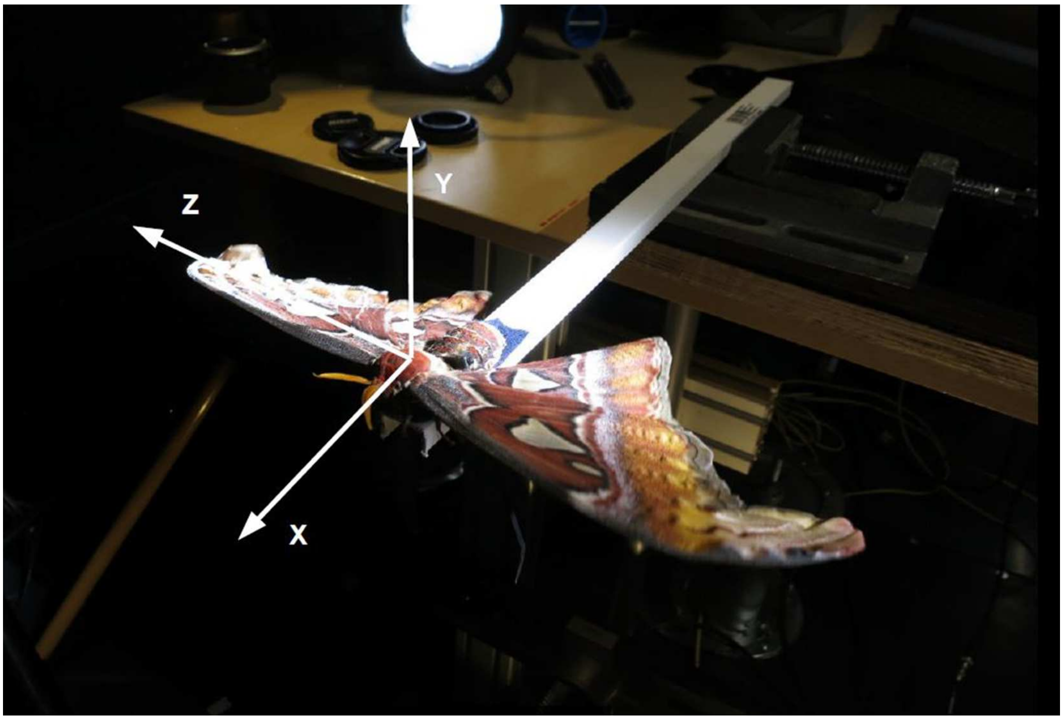

Fig. 2. The adopted coordinate system

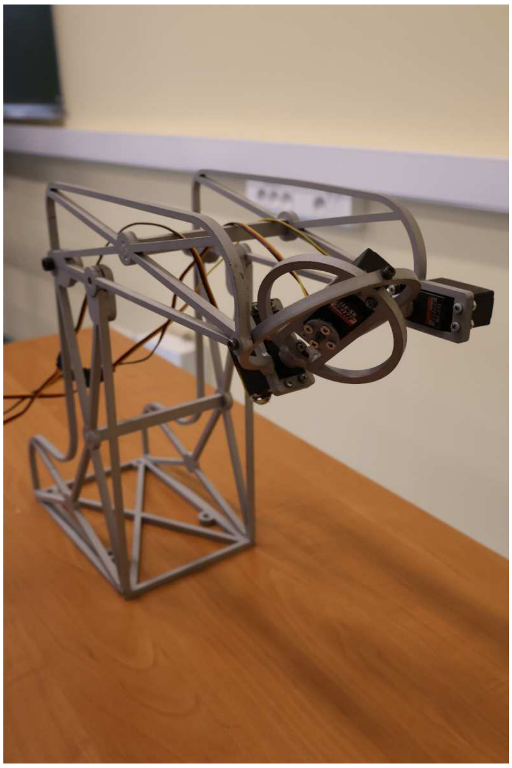

Fig. 3. The wing model control mechanism

for rotation around a different axis. One was located on the axis of rotation and the other two rotated the hoops (see Fig. 3). This solution enabled the implementation of trading at a point. It is possible to tilt the entire arm to temporarily remove the model from the liquid. The whole structure is attached to the plate on which the liquid container is placed (Fig. 4). The places where the pressure difference is measured are marked with red arrows in Fig. 4. The rotation of the servomotors around the axis was programmed based on the Arduino IDE software.

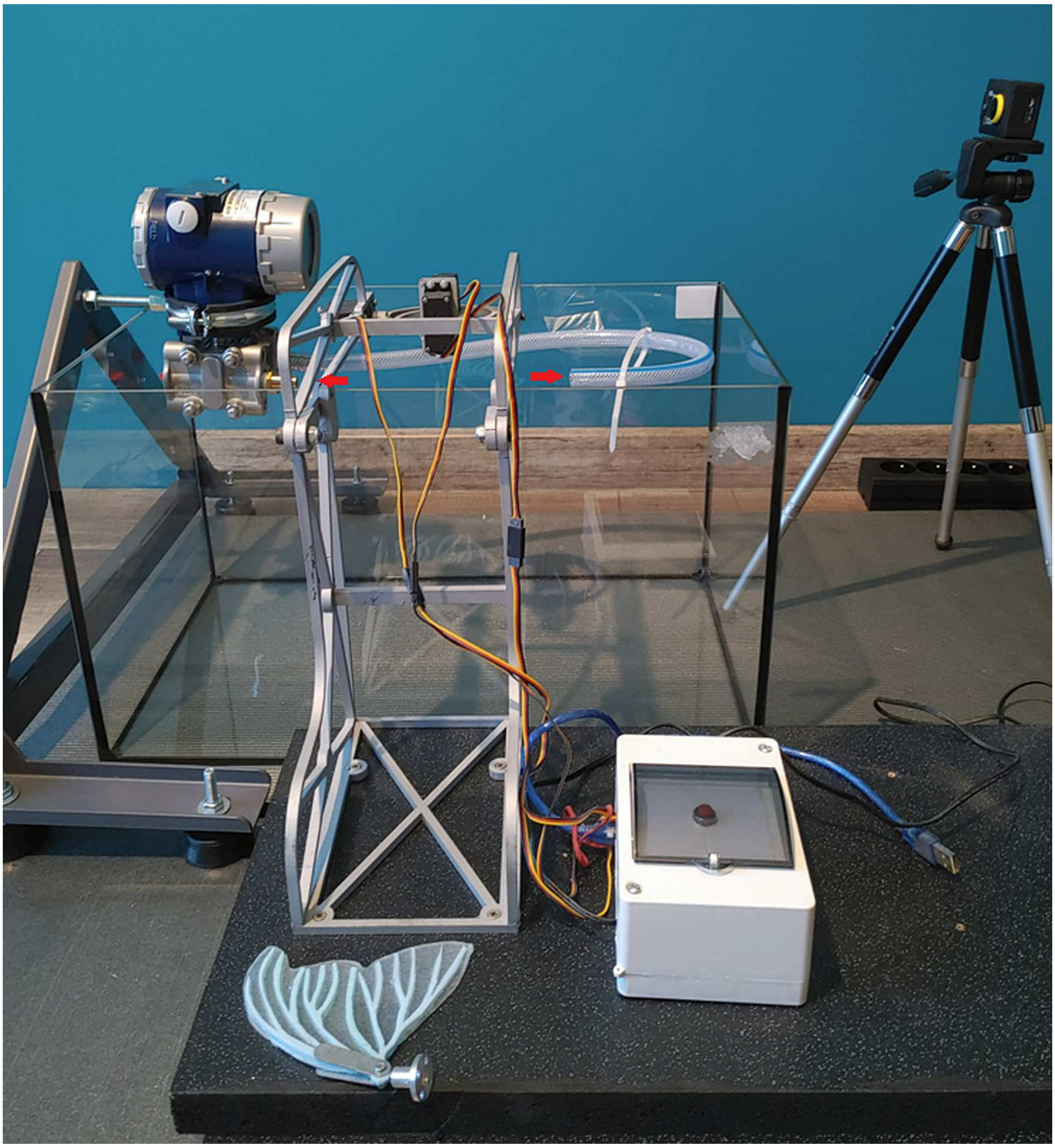

Fig. 4. View of the experimental stand

A single stroke cycle of the wing was initiated by pressing the trigger button. Repetition of the cycle required another button pressing. As the system was located in a very dense and viscous liquid, the influence of gravity on the behaviour of the liquid could be neglected, and thus the wing could be arranged in the liquid in any (from a pragmatic point of view) position. The adopted coordinate system was marked directly on the container and is visible on the recording. The centre of the coordinate system is the same as in the previous numerical analysis (Kunicka-Kowalska *et al.*, 2022a).

3. Results

The wing deflection was measured as the angle of deviation of the plane of the deformed wing from its original position for the same time instants. The wing deflection observed in the original movement (experimental data) was 18 degrees. This shows a significant convergence of the observation of a living object with numerical calculations (19 degrees) and an experiment with the real model (17 degrees). This stage was a form of verification of the correctness of both the calculations and the silicone model itself. After observation and visual analysis, the test stand was expanded by adding a differential pressure sensor (BD Sensors DPT 200 XMD, Warszawa, Poland). The sensor (accuracy: 0.075% of the range) registered the pressure difference in front of and behind the wing in the case of thrust measurement, and above and below the wing in the case of lift measurement. The sensor was placed in the immediate vicinity of the tested object, and a high viscosity of the fluid was a guarantee of moderate diffusion of the phenomenon. All validation measurements, as well as measurements of movement and pressure for subsequent modifications, were recorded with a camera.

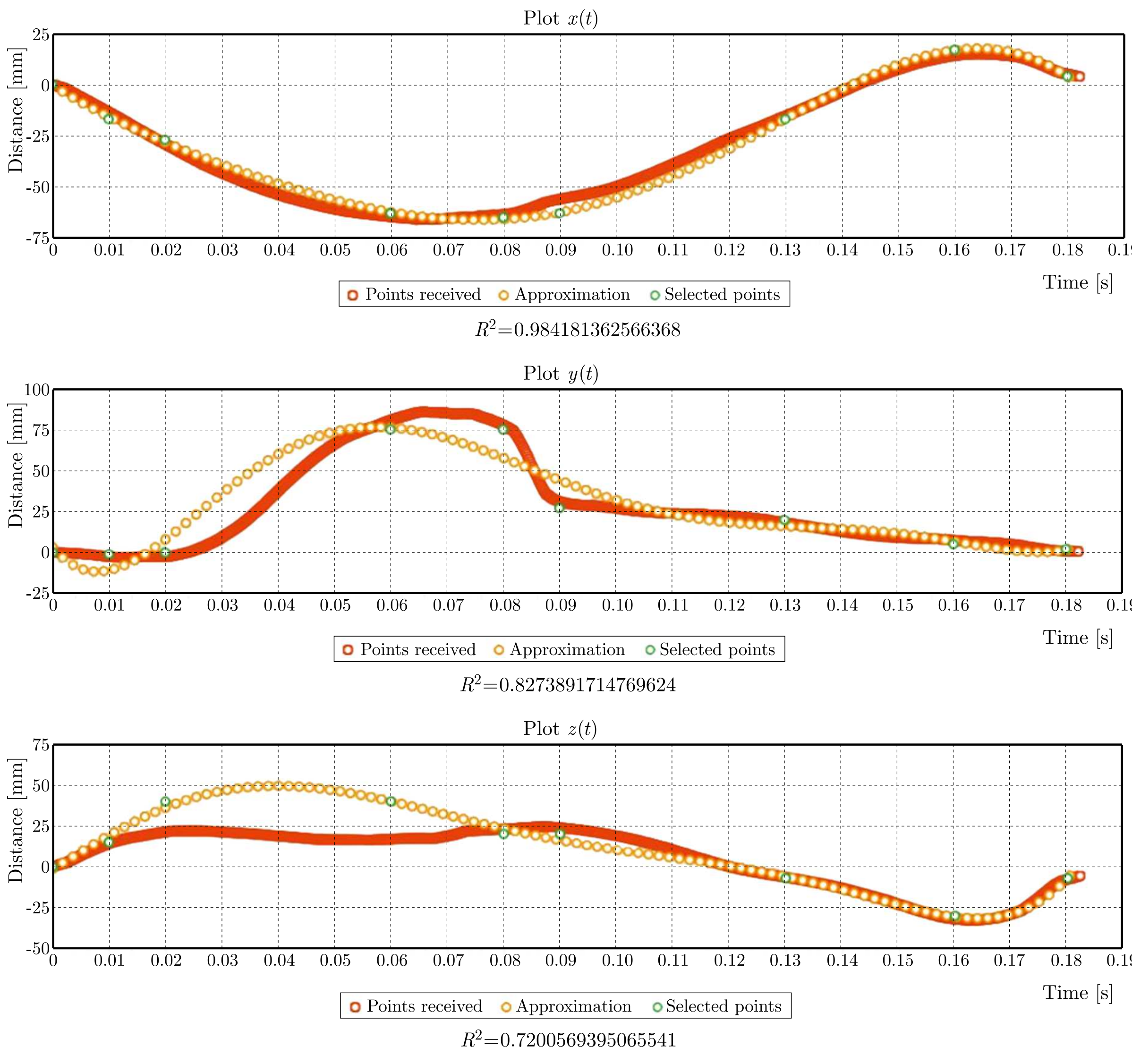

Fig. 5. Modification of wing rotation as a function of time, version A

During the experiment, a number of modifications to the rotational movement of the wing were then introduced. The modifications were introduced to demonstrate how changing rotation at a specific stage of stroke affects the pressure differential. These modifications were introduced by moving the plot points in the Stirling program (approximation software). The algorithm then adjusted the course of polynomial curve, thus correcting the original motion. The most important modifications are listed below:

- modification A – increasing the angle of attack during the climb phase: the potential benefit should be an increase in the lift by obtaining greater dynamics of the leading edge vortex (LEV);
- modification B – reduction of the angle of attack when the wings move backwards: the expected effect would be an increase in the thrust as a result of increasing the wing area during push-back;
- modification AB – combination of modifications A and B, i.e. a simultaneous increase of the angle of attack during the climb phase and a decrease when the wings move backwards: in this case, it was expected to obtain both increased lift and thrust;
- modification C – modification of experimental data by adjusting the function to the literature data (Shyy *et al.*, 2007): the aim was verification;
- modification CB – combination of modification B (reduction of the angle of attack when the wings move backwards) in the first part of the graph, and modification of C (Shyy *et al.*, 2007) in the final part of the function.

For example, the modification of rotation in version A with time is shown in Fig. 5. The orange points show the primary kinematics of the butterfly wing. The measurement of the actual wing rotation was made based on photos from a high-speed camera, the data includes 912 points during one wing stroke (Kunicka-Kowalska, 2020).

4. Discussion

The mathematical description of the wing rotation was implemented in the program controlling the servomotors via Arduino. The obtained results of the pressure difference change over the cycle and are shown in the graphs (Figs. 6 and 7). Table 2 shows the total pressure difference in the cycle. Positive values show positive strength. Due to the high frequency of the wing impact, the total pressure difference in the cycle can be considered as a single impulse. However, this value as a function of time shows the influence of particular phases of wing movement (and therefore also their modification) on the final effect in the form of aerodynamic forces.

Table 2. Total pressure difference in the cycle for various modifications pressure difference [mbar]

Pressure difference [mbar]	Tsst	Mod A	Mod B	Mod AB	Mod C	Mod CB
Thrust	−0.651	−0.083	0.069	−0.045	−0.093	−0.148
Lift	0.022	0.108	0.138	2.14	0.075	−0.033

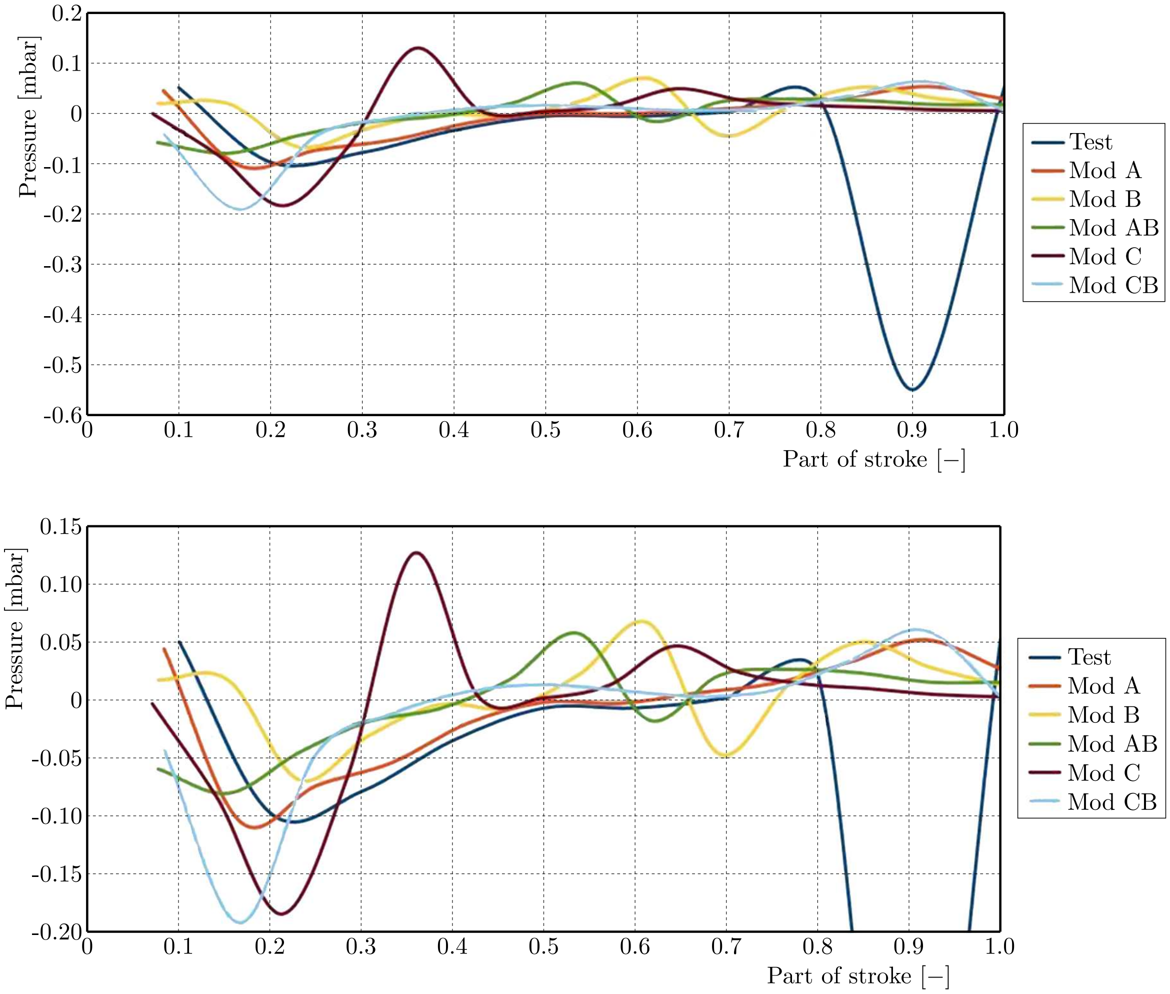

Fig. 6. Pressure difference in front of and behind the wing during one stroke for individual modifications (thrust) [mbar]

5. Conclusions

According to the previous research (Kunicka-Kowalska *et al.*, 2022b), the thrust is generated by the shape of this wing itself, but it is small. The research has shown that only increasing the wing angle of attack produces thrust. Moreover, increasing the stroke amplitude does not have a positive effect on the increasing thrust. However, the initially large angle of attack increases the thrust in the wing descent phase. This has a direct impact on the increasing of pumping effect (creating an air cushion under the wing), but also increases the frontal area when raising the wing. Thus, the original position of the wing at rest is of great importance.

The most important conclusion regarding the measured pressures that influence the lift is that increasing the angle of attack while raising the wing increases the LEV energy and thus increases the lift. In the second phase of movement, the mentioned angle of attack influences the use of resulting air cushion to generate the lift force. Based on the analyses, it was found that AB modification contributes to a significant increase in the lift while reducing the thrust – it can be used as a temporary, very energy-consuming procedure. Modification C, on the other hand, is the closest to hovering. CB modification does not bring the expected physical effects.

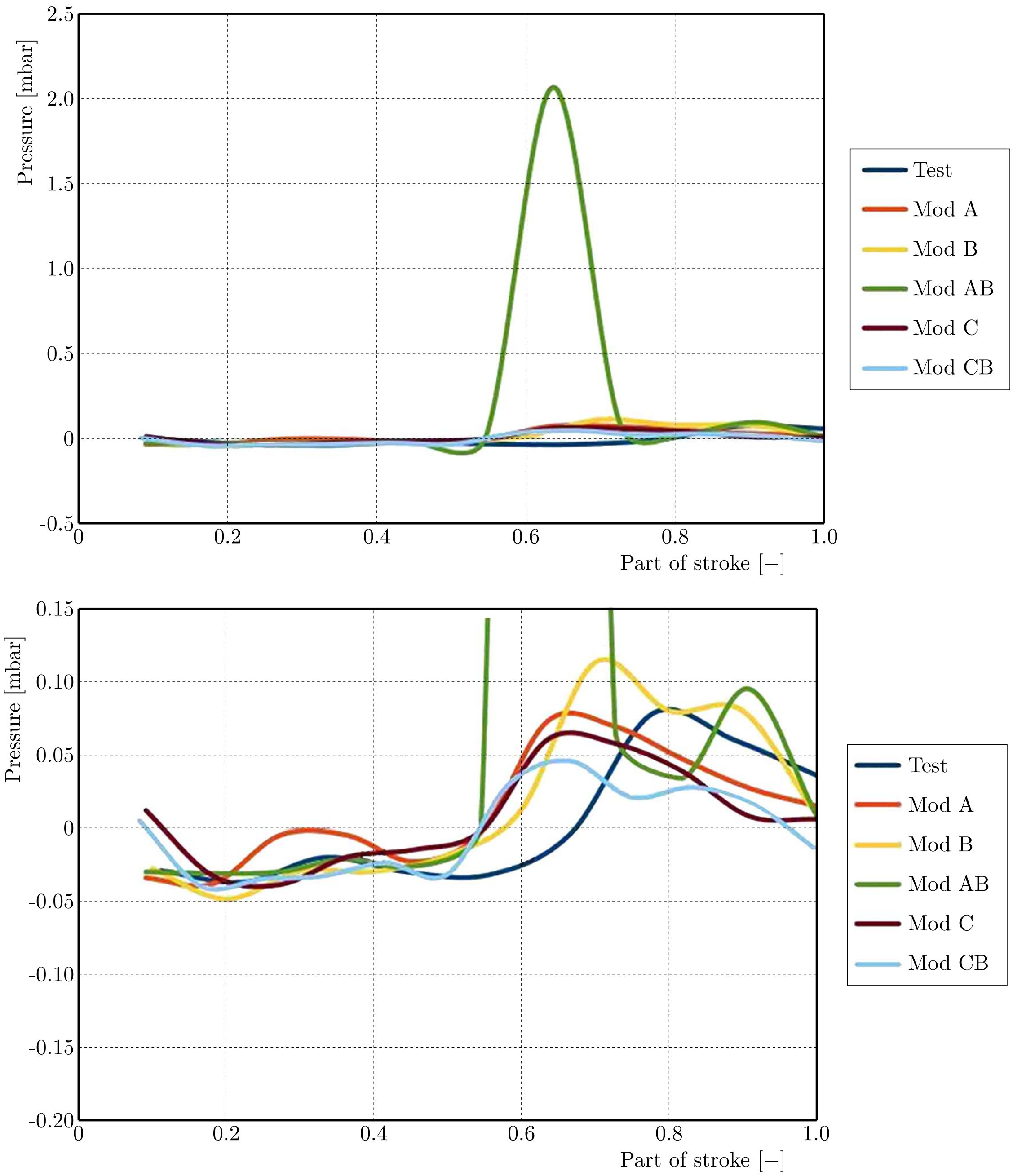

Fig. 7. Pressure difference above and below the wing during one stroke for individual modifications (lift) [mbar]

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References

1. Aditya K., Malolan V., 2012, *Investigation of Strouhal Number Effect on Flapping Wing Micro Air Vehicle*, https://doi.org/10.2514/6.2007-486 [18.06.2012]
2. Biej-Bijenko G.J., 1976, *Introduction to Entomology* (in Polish), Powszechne Wydawnictwo Rolnicze i Leśne, Warsaw, Poland

3. Bluman J., Kang C.-K., 2017, Achieving hover equilibrium in free flight with a flexible flapping wing, *Journal of Fluids and Structures*, **75**, 117-139
4. Ellington C.P., 1984, The aerodynamics of hovering insect flight I-VI, *Philosophical Transactions of the Royal Society B*, **305**, 1122, 1-181
5. Fry S.N., Sayaman R., Dickinson M.H., 2005, The aerodynamics of hovering flight in *Drosophila*, *Journal of Experimental Biology*, **208**, 12, 2303-2318
6. Ha N.S., Jin T.L., Goo N.S., Park H.C., 2011, Anisotropy and non-homogeneity of an *Allomyrina Dichotoma* beetle hind wing membrane, *Bioinspiration and Biomimetics*, **6**, 4, 046003
7. Hu Y., Wang J., 2010, Experimental investigation on aerodynamic performance of gliding butterflies, *AIAA Journal*, **48**, 10, 2454-2457
8. Hu Y., Wang J., Zhang P.F., Zhang C., 2009, Experimental investigation on the flow structure over a simplified Papilio Ulysses model, *Chinese Science Bulletin*, **54**, 6, 1026-1031
9. Kunicka-Kowalska Z., 2020, Modeling the flow around the insect flapping wing on the example of the butterfly Attacus atlas, PhD Thesis, Warsaw University of Technology, Warsaw, Poland
10. Kunicka-Kowalska Z., Landowski M., Sibilski K., 2022a, Deformable model of a butterfly in motion on the example of Attacus atlas, *Journal of the Mechanical Behavior of Biomedical Materials*, **133**, 105351
11. Kunicka-Kowalska Z., Landowski M., Sibilski K., 2022b, The motion analysis of *Attacus atlas* rigid wing, *International Review of Aerospace Engineering*, **15**, 4, 205-214
12. Kunicka-Kowalska Z., Sibilski K., 2018, Study on Attacus Atlas wing motion during flapping flight for needs of FEM simulation (in Polish), [In:] *Mechanika w Lotnictwie, ML-XVIII 2018*, **II**, K. Sibilski (Edit.), Polish Society of Theoretical and Appplied Mechanics, Warsaw, 35-43
13. Landowski M., Kunicka-Kowalska Z., Sibilski K., 2020, Mechanical and structural investigations of wings of selected insect species, *Acta of Bioengineering and Biomechanics*, **22**, 2, 199-209
14. Okamoto M., Sunada S., Tokutake H., 2009, Stability analysis of gliding flight of a swallowtail butterfly *Papilio xuthus*, *Journal of Theoretical Biology*, **257**, 2, 191-202
15. Piechna J., 1997, How do animals fly? (in Polish), *Wiedza i Życie*, **8**, 24-29
16. Reade J., Jankauski M.A., 2020, Deformable blade element and unsteady vortex lattice fluid-structure interaction modeling of a 2D flapping wing, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, **83969**, American Society of Mechanical Engineers
17. Senda K., Obara T., Kitamura M., Nishikata T., Hirai N., *et al.*, 2012, Modeling and emergence of flapping flight of butterfly based on experimental measurements, *Robotics and Autonomous Systems*, **60**, 5, 670-678
18. Shyy W., Lian Y., Tang J., Viieru D., Liu H., 2007, *Aerodynamics of Low Reynolds Number Flyers*, Cambridge University Press, Cambridge, UK
19. Steppan S.J., 2000, Flexural stiffness patterns of butterfly wings (Papilionoidea), *The Journal of Research on the Lepidoptera*, **35**, 61-77
20. 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

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