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Multi objective design an artificial wing of micro air vehicle inspired of insect wings

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Connecting point of the longitudinal veins and cross-veins in wing is called Joint. In some insect wing joints, there is a type of rubber-like protein called Resilin. Due to the low Young's modulus of this protein, its presence in the wing can help to change the shape of the wing during flight. Today, using composite structures in flying vehicles in order to achieve the desired shape of wing is considered. The purpose of this study is the multi-objective optimization of artificial wing by arranging Resilin joints in the artificial wing of Micro air vehicles (MAVs). The amount of torsion and bending of the flapping robot wings is considered as the objective function to improve the flight performance of robots. Two types of artificial wings have been investigated, and considering pareto points, the optimal arrangement of Resilin joints has been achieved. The result of this study shows that in both wings, with the presence of Resilin in the joints, the amount of torsion has increased to 38.65 degrees.

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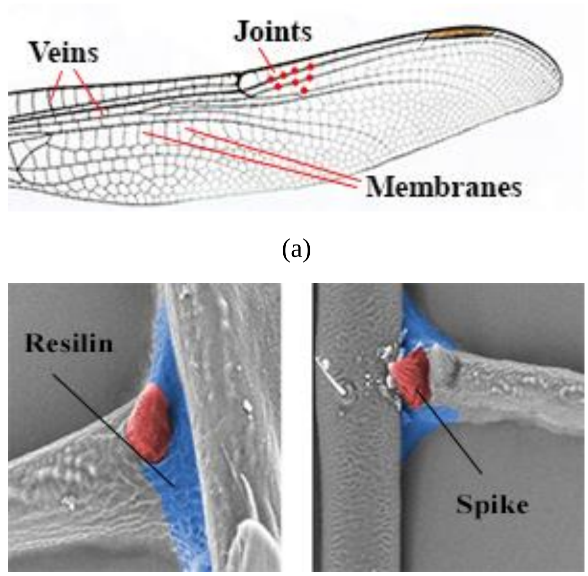
1. Introduction

Today, there is a great desire to develop MAVs and flying cars. These robots have a lot of potential for transportation, collecting information in the field of environmental monitoring, national security and other purposes [1]. These robots have been developed by modeling the flight of insects [2,3]. Insects have many flying abilities, such as flying motionless, taking off, flying backwards, and flying sideways [4]. Dragonflies, meanwhile, are clearly superior to all other large insects. They have the ability to accelerate and maneuver very quickly in very small spaces [5]. Dragonflies can reach high speeds with low energy consumption. Many of these capabilities can hardly be built in man-made flight systems [4]. All of these abilities are caused of their unique wing shape. The wings of dragonflies have basically archaic design. However, they are complex structures capable of controlled torsion, which is essential for flapping flight. Amount of torsion, twist and bending of the wings has effects on insect flight performance [6]. The wings of dragonflies have a special structure and light weight with high deformability. However, they have a high resistance to forces and large deformations that occurs in air collisions [7]. To the best of our knowledge, the influential features in Udonata wing deformity are classified as: heterogeneous material distribution [8], non-uniform thickness [9], vein patterning [10], corrugation [11], joints [12], Spikes [13], Resilien [14], Vein microstructure [15]. Therefore, it is important to understand the role of each of these factors in the wings of dragonflies to make similar artificial wings more efficiently.

Veins and membranes are the main components of a wing [1]. In Figure 1a, veins and wing membranes can be seen in different areas. The veins have a hollow structure and geometrically have different shapes in different parts of the wing [15]. The membranes are also very thin in most parts of the wings [9]. Veins can be structurally divided into three categories: (1) thick longitudinal veins that extend from the beginning to the end of the wing, (2) thin, short cross-veins that connect adjacent longitudinal veins to each other, and (3) the wing margin veins [15].



(a)

(b)

Figure 1: Components of a wing: (a) Sample of vein, membrane and joint; (b) Location of resilin

As mentioned, joints are one of the most important elements in insect wings. In fact, they are where the longitudinal veins and cross-veins connect. The morphology of the connections between the longitudinal veins and cross-veins of the dragonfly wing was first described by Newman [12]. He categorized these vein joints into two main groups, flexible and inflexible joints, and suggested that they could contribute to the inactive deformation of insect wings. The effect of flexible joint shape on the performance of dragonfly wings is more seen in the works of Wooton and Newman [16]. There are generally two types of joints in dragonfly wings: movable and immovable [17]. Some longitudinal veins are elastically attached to the cross-veins while other longitudinal veins are firmly attached to the cross-veins. Resiline is a type of rubber-like protein found in the flexible junctions of dragonfly veins [6]. Figure 2b shows location of resilin. This protein is responsible for storing elastic energy [18]. This protein has also been observed in the beetle jump system [19], fleas [20] and dragonfly flight muscle tendons [18]. The distribution pattern of resilin in the dragonfly wing is one of several mechanisms that are responsible for involuntary movements of the wing [6].

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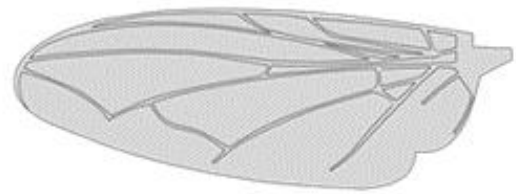
2.Geometrical model

In this study, 2 artificial wings, made for flapping robots, were used [21]. Finite element model of two wings is obtained by Wing gram software by accurate image processing with full geometrical details of veins and membranes [22, 24]. Figure 2 shows the images of Physical models of wings [21]. Geometrical wings made by Wing gram, are shown in Figure 3. Figure 4 shows models analyzed by Abaqus software and In Figure 5 models that made by 3D printer can be seen. Length of printed wings are 10 cm. Due to the very low amount of tensile strength and elasticity coefficient of resilin compared to the main material forming the longitudinal and cross-veins in the models printed by the 3D printer, the resilin joint is modeled by empty circle on it. Sample of printed wing with resilin in joints shown in figure 6. In this way, the effect of Resilin can be seen in the joints, and it also makes it possible to make an artificial wing with flexible joints by simple devices. Figure A shows an example of the first printed wing with Resilin joints. Figure b shows the printed wing finite element model. Also, in figures A and B, an example of the second artificial wing has been printed and modeled, considering Resilin in some joints.

(a)

(b)

Figure 2: Physical models Ref [21]: (a) Artificial wing number 1; (b) Artificial wing number 2.



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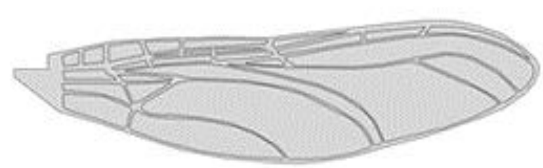
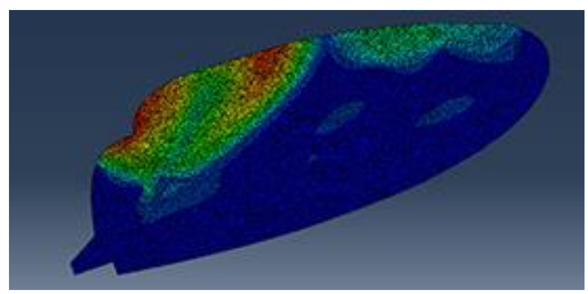


(b)

Figure 3: Geometrical model of wings made by wing mesh: (a) Artificial wing number 1; (b) Artificial wing number 2



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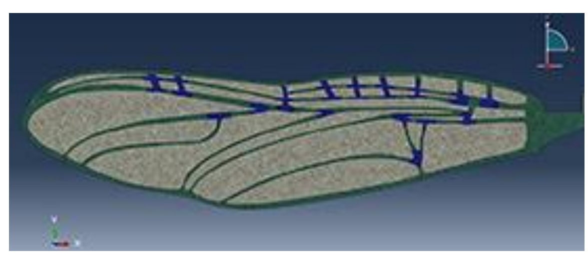

(b)

Figure 4: model of wings in Abaqus software: (a) Wing NUM 1; (b) Wing NUM 2

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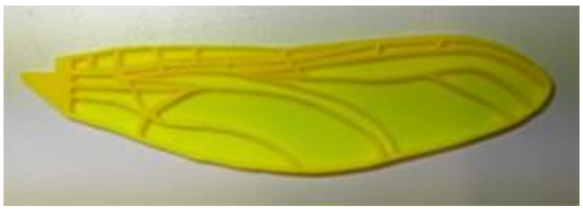
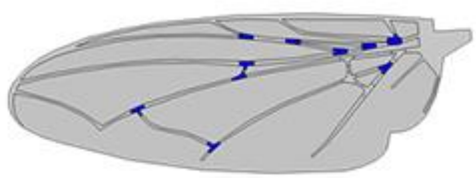
(a)



(b)

Figure 5: Printed 3D model of wings: (a) wing NUM 1; (b) wing NUM 2

(a)



(b)

Figure 6: modeled wing with resilin in joints (a) 3D printed model; (b) finite element model

3.Loading and boundary conditions

In this study, two types of loading have been used, the first loading is a point force to determine wing displacement and it is used to validate the model, built by codes in Matlab-Abaqus and printed model. The artificial printed wings tested by the Zwink machine available in the biological laboratory of the University of Kiel, Germany, which has the ability to apply loads from 0.05 to 500 newton with 0.01 mm Measurement accuracy in displacement. The image of the used device can be seen in Figure 7. The average calculated error between the modeled wing and the laboratory test is reported to be 6.08%. The second loading, which is the desired loading for optimal wing design, is the application of a uniform pressure load with a value equal to 90 Pa for two wings. In both types of loading, the beginning of the wing is considered completely fixed according to Figure 8. A biomimetic wing should be very light and requires a flexible and durable shell that includes hard and light veins. PLA has been used to simulate the veins and membranes. Mechanical properties of the veins, membranes and resilin for analyzing finite element model, can be seen in the table 1.

Figure 7: Zwink mechine in biological laboratory Kiel Germnay

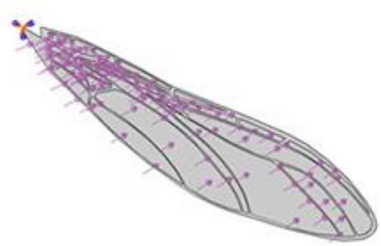


Figure 8: Uniform pressure loading and boundary condition

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Table 1: Mechanical properties of modeled wing

Part of wing	Density kg/m^3	Young modulus Gpa	Poisson's coefficient
Vein Membrane	1240	2.9	0.3
Resilin	1200	0.002	0.49

4.Optimization

The presence of Resilin in the joints has a great effect on the shape change and also the amount of twisting and bending of the whole wing. The purpose of this research is to design and optimize two artificial wings to use in flapping robots and also to investigate the effect of the presence and location of Resilin joints on the performance of artificial wings. In this research, the finite element models of the wing made by the Wing gram software were created by image processing and then optimized by the multi-objective uniform-diversity genetic algorithm (MUGA) [23], and the finite element software abaqus was used to analyze the determine total displacement and deformation of the wing It has been used to the calculate twisting and bending. In Figure A, the modeled wing can be seen in the Wing gram software, and also in Figure B and C, the wing is meshed and the results of the analysis in abaqus software are shown. The obtained models were loaded by uniform pressure and their amount of twisting and bending was calculated. The resilin area is considered to be a circle with a radius of 3 mm and resilin material was applied at selected points, and the modeled wings were subjected to a uniform pressure load during optimization. Then, each of the two wings is optimized by MUGA. Two objective functions are minimum amount of overall bending of the wing along the axis and the maximum amount of torsion of the wing. In the flight of flapping robots inspired by insects, torsion causes more air to move back of the MAV and this leads to more thrust. Also, high bending causes a decrease in the effective flapping area of the wing, and decrease in the volume of displaced air in each stage of flapping. In general, it can be considered that the higher the number of flexible joints in the wing, increase the total twist of wing. But, it causes a high increase in the bending of the wing; in fact, the flying efficiency of the artificial wing will be lost. With the reduction of flexible joints, the amount of bending of the wing is reduced, which will have a positive effect on volume of displaced air, but the amount of wing torsion will reach its lowest amount, which will reduce the thrust of the MAVs. For this reason, multi-objective optimization by MUGA been used to find optimal pareto diagram to find a trade point that can provide both objective functions. Optimizing algorithms leads to reach the minimal value of cost functions. But in this research, maximizing the torsion or highest amount of the first objective function is aimed. Therefore the first objective function is multiplied by -1. The optimization design variables are considered as 0 and 1, where 0 means absence of Resilin and 1 means existing of Resilin in that joint. The number of variables is 14 for the first wing and 23 for the second wing according to figure 9.

5.Results and discussion

Two studied artificial wings have been subjected to two-objective optimization in order to achieve the highest amount of torsion and the lowest amount of bending simultaneously. As mentioned before, by Wing gram image processing software, the geometric structure of the studied wings along with the mesh information has been taken for use in optimization. Then, by establishing the connection between MATLAB code and ABAQUS software, using python scripts, each created sample wing, is analyzed by knowing the location of resilin joints. So, the resulting displacements are read by MATLAB code, and the overall amount of torsion and bending of the wing is calculated automatically, to continue the optimization process. This process will continue until reaching the end of optimization. At the end, the obtained Pareto diagram points are optimal design points that the user can use any of the wings presented in the diagram according to the desired goal.

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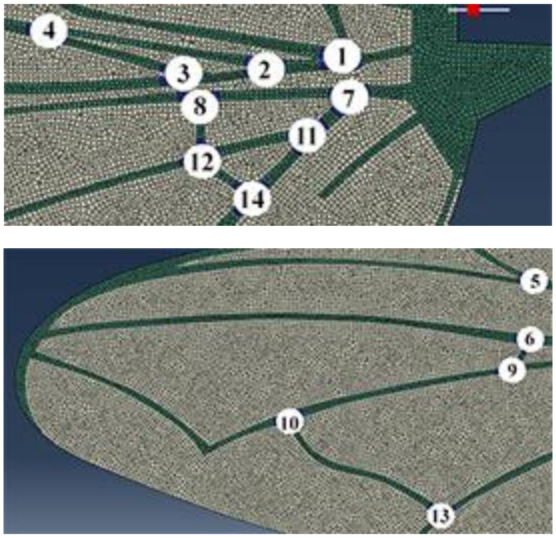

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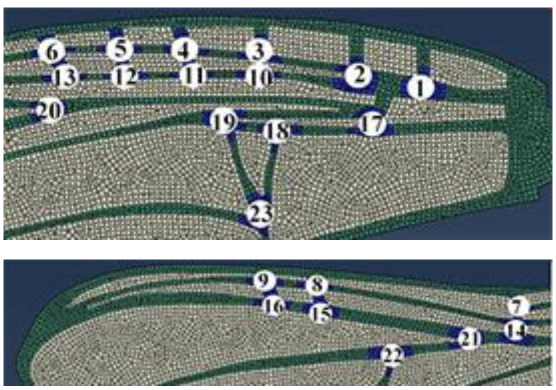

(b)

Figure 9: Joint number of wings: (a) Wing NUM 1 (b) Wing NUM 2

First case:

The optimization of the artificial wing joints in the case of the first wing has been done with MUGA. The Pareto diagram resulting from the optimization can be seen in the Figure 10. All points in the diagram are considered optimal design points. Among the Pareto points, points A, B and C have been investigated due to the importance of the target value. Point A has the highest value from the point of view of the first objective function or the torsion value. But from the point of view of the second objective function, it is not desirable compared to other points, and point B is considered the best design point for the second objective function, which has the minimum amount of bending. Each of the points A and B can be considered as a single-objective solution for the objective function of the maximum twist and the objective function of the minimum bending. respectively. In this research, the design point C, which is located in the broken point of the diagram, was considered as the optimal design point for two objectives. The values of the objective functions of each of the three desired points are shown in the table 2.

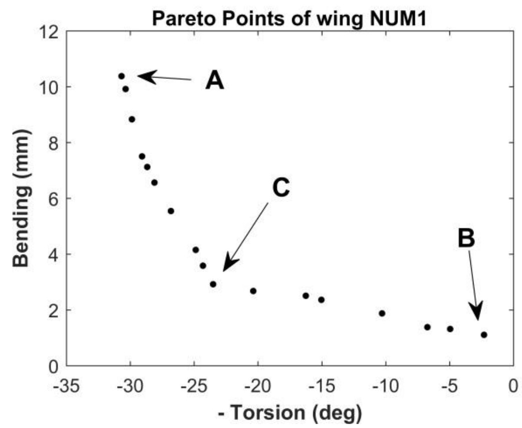

Figure 10: Pareto point of optimization of first wing

Table 2: Objective function and design variables of optimization of artificial wing number 1

Design point	Torsion (deg)	Bending (mm)
A	30.69	10.37
B	2.29	1.102
C	23.51	2.92
	Joint with resilin	
A	2 4 5 6 7 8 9 12 14	
B	8 10 13	
C	3 7 9 10 11 12 13 14	

Second case:

The artificial wing considered in this optimization has more joint locations than the first case. The number of desired wing joints that have a suitable position for the presence of Resilin is 23. The results of the two-objective optimization are shown in the Figure 11. Points D and E can be considered as single-objective optimal points, as it can be seen that the design

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point D has the best layout of the meshes with Resilin from the point of view of the twisting objective function. Also, point E has the best arrangement of Resilin from the point of view of the bending objective function. The design point F is considered as the optimum point of optimization. The arrangement of Resilin in this optimal point has made the two objective functions to have their optimal value at the same time. The obtained objective function values for the three considered points are specified in the table 3.

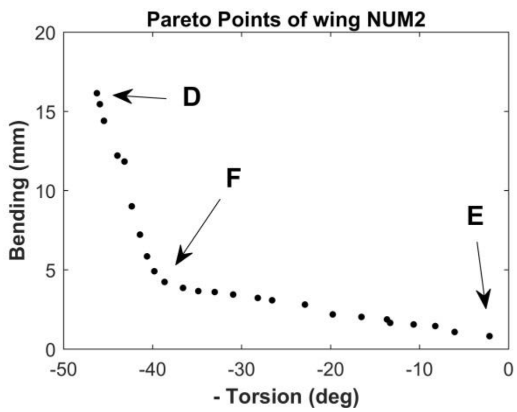

Figure 10: Pareto point of second case

Table 3: Objective function and design variables of optimization of artificial wing number 2

Design point	Torsion (deg)	Bending (mm)
D	46.26	16.14
E	2.131	0.81
F	38.65	4.22
	Joint with resilin	
D	2 5 6 7 8 910 11 12 14 15 18 19 20 21 22 23	
E	2 3 12 14 18	
F	12 13 14 15 16 17 19 20 21 22 23	

6.Conclusion

The results of this study show the presence of Resilin in artificial wings will have a great effect on the flight performance of flapping robots. The use of multi-objective optimization in choosing the optimal position of resilin in joints increases the efficiency of MAVs. It also provides a range of optimal wings to the designer, so that the user can choose one of the optimal points for manufacturing an artificial wing according to the goals pursued. In the case of the first artificial wing, 8 resilin joints with optimal arrangement have increased the amount of twist by 22.31 degrees and the amount of bending by 1.96 mm only compared to the state without Resilin. Also, in the artificial wing of the second study, according to the optimization results and design point F, out of 23 existing joints, 11 joints have been considered with Resilin, which has increased torsion by 37.05 degrees and only increased bending by 3.72 mm. And these values show the improvement of the flight performance in the artificial wing with the attitude of optimal arrangement of Resilin in the joints compared to the state without Resilin. It should be noted that the design of artificial wings inspired by insect wings, will help researchers a lot. According to the results of this research and the comparison of the optimal wing with the wings of insects in nature, it was observed that the structure of flexible joints are seen more in the back area of insect's wing which can be useful for long journeys. And in the front edge of the wing, the joints show less flexibility. In the results obtained, which were performed on two artificial wings, it was also seen that in the optimal wing, the joints with Resilin in the front edge of the wings are less than the rear area of it. Of course, the wing structure of insects also serves other purposes. But it can be said that the result of optimizing the flight performance of insects shows the power of engineering and design of the creator of the universe in the field of passive wings. It is also worth noting that Resilin structures can be used to create a desired deformation in the face of pressure or impact loading in order to maintain safe areas such as the location of passengers in the car, or any other shelters.

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