Conceptual design and parametric structural modeling of a FWA V biomimetic flapping wing

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Abstract. Flapping wing air vehicle is the latest technological achievement of the aviation industry, which is still maturing as a miniature of large aircraft before finally achieving the finest development. By mimicking the nature, parametric structural modeling of a flapping wing, made of composite membrane and aluminum alloy support beam is numerically investigated adopting commercial FE code Ansys. A flapping cycle is divided into twelve segments, and for each segment, the maximum stress, first ply failure and the deformation are studied. It is found that the fiber orientation angle has the highest impact on the structural properties during a flapping cycle, where improper stacking sequence will cause failure to the wing. Moreover, increasing the ply thickness has a positive impact on the overall structural performance of the model. Finally, appropriate support beam orientation can further improve the structure by increasing the stiffness and reducing the maximum stress significantly without increasing the overall weight of the wing.

1. Introduction

Flapping wing air vehicles (FWAV) have already gained popularity in the aviation industry due to their multiple applications in both civil and military sectors. However, despite technological advancements and scientific insights, the domain remains uncharted, and the current research works are mainly conducted based on the trial-and-error method [1]. Overall, the ongoing advancements of FWAV research can be divided into two major branches: i. Investigation of the flight mechanism, aerodynamics and wing structure of flying animals like insects and birds and ii. Development of theoretical models and applying them to flying robots by mimicking nature.

In nature, large birds use steady aerodynamic principles for their flight. In contrast, insects and smaller birds use more complex unsteady aerodynamic mechanisms like clap and fling mechanism, delayed stall and wing rotation, wake capturing, and asymmetric flapping [2]. A brief review of the aerodynamic phenomena of insect and bird flights can be found in [3-6]. Other notable contributions are mainly focused on the determination of optimal lift, thrust, and efficiency of flapping wings using both experiments and computational fluid dynamics [7-10]. Furthermore, development and successful flight testing of full-scale stable FWAV are achieved for various applications [11-13].

Even though numerous attempts were made to understand the unsteady aerodynamic behavior of the flapping wings, which is undoubtedly the most challenging task to unveil the flight mechanism, in contrast, very few research has been carried out to learn the structural performance, which also plays a great role in generating successful flapping. To investigate the structural properties of the Calliphora wing, both experimental and numerical studies were performed, and it was revealed that the mass per unit length is higher in the wing root and decreases towards the wing tip [14]. A more detailed structural analysis was carried out using a micro-CT scanner on Dragonfly wing, which unveiled that...
the vein and membrane thickness increases from tip to root, allowing the wing to bear both inertial and aerodynamic loads effectively [15]. Inspired by nature, a three-dimensional solid structural submodel of dragonfly forewing is created, and the Finite Element Method (FEM) is employed to find the stress distribution and deformation pattern of the model [16]. It was found that the maximum stress in the chitin layer is larger than that in the protein layer.

To validate the experimental flowfield and deflection measurements of an insect based flexible flapping wing, coupled computational fluid dynamics solver based on unsteady Reynolds-averaged Navier-Stokes (URANS) equations and computational structural dynamics solver capable of modeling nonlinear beam and shell element is adopted [17]. Overall, the CFD-CSD results showed good agreement with the measured experimental flowfield and wing deformation data.

Based on the three-dimensional unsteady vortex lattice method (UVLM), a bio-mimetic flapping wing was tested using FEM for three different material models; namely, linear, composite and Mooney-Rivlin model. It was found that the composite and the Mooney-Rivlin nonlinear models produce significantly lower stress compared to the linear elastic model [18]. Other notable bioinspired wing designs can be found in [19-21], and parallel research works on the control system mechanism can be found in [22].

The present investigation describes parametric structural modeling of a bio-mimetic flapping wing made of carbon-epoxy composite material and aluminum alloy. Firstly, a 3D wing model is developed, and downstroke and upstroke forces are calculated on the wing based on the UVLM method. Then the effect of fiber orientation angle on the flapping wing structure is investigated. Besides, the influence of laminate thickness and support beam thickness is also studied. Finally, the support beam orientation is examined on the structural performance of the wing model.

2. Theoretical Formulation

A flapping cycle is divided into 12 segments, and for each segment, both aerodynamic and inertial forces are calculated on the wing, dividing it into 32 elements. The aerodynamic force is calculated based on the three-dimensional UVLM method [23], which is given as follows.

$$\Delta F_y = -(\Delta P \Delta S)_y$$  \hfill (1)

where $\Delta P$ is the pressure of the element and $\Delta S$ is the area of the element.

The periodic inertial force, generated from the acceleration and deceleration of the flapping wing, is one of the main acting loads during each cycle. The calculation formula of inertial force on each element during a specific flapping segment can be expressed as follows.

$$F_i(t) = \omega^2 m_i r_i \beta_{max} \cos(\alpha t) = \omega^2 \rho_i \beta_{max} A_i r_i \cos(\alpha t)$$  \hfill (2)

where $F_i(t)$ is the inertia force of element $i$, $m_i$ is the mass of element $i$, $r_i$ is the rotational radius of element $i$, $\omega$ is angular velocity, $t$ is time, $\beta_{max}$ is the amplitude of flapping angle, $A_i$ is the area of the element and $\rho_i$ is the material density.

To calculate the failure criterion of the composite flapping wing, Tsai-Wu failure theory is adopted [24].

3. Finite Element Setup

3.1 Flapping wing modelling

A conceptual 3D model of the flapping wing is developed using Ansys CAD modeler, shown in figure 1. The semispan of the wing is 320 mm long, and the maximum chord length is 100 mm. The membrane is 1 mm thick, which is supported by 9 vertical and 1 horizontal beam, forming a support beam system connected beneath. Both the width and thickness of each beam are 1 mm. Other important parameters that are mainly used to calculate the force acting on the membrane surface are flapping frequency = 8 Hz, flight velocity = 11 m/s, flapping angle = 45° and the angle of attack = 5°.

Since the biological material of bird wing shows a viscoelastic behavior after mechanical treatment [25], for modeling the membrane, carbon-epoxy is chosen, which are viscoelastic materials that...
exhibit creep and delayed failure [26]. The detailed mechanical properties of carbon-epoxy composite material with failure stress can be found in [27]. The support beam system is assumed to be isotropic since bone can be modeled as isotropic material from the nanoscale level in FEM [28] and a widely used aerospace aluminum alloy (Al-2024-T4) is adopted for beam modeling with linear properties [29].

To investigate the effect of fiber orientation angle on the structural properties of the wing model; namely, failure, maximum stress, and deflection, an 8 ply laminate with various configurations including quasi-isotropic, angle-ply, and cross-ply symmetric layers are considered. The investigated lay-ups are given as follows.

- **Quasi Isotropic Laminates**: \([0^\circ/45^\circ/-45^\circ/90^\circ]_s, [90^\circ/0^\circ/45^\circ/-45^\circ]_s, [0^\circ/90^\circ/45^\circ/-45^\circ]_s\)
- **Cross-ply Laminates**: \([0^\circ/90^\circ]_{2s}\)
- **Angle-ply Laminates**: \([\pm 30^\circ]_{2s}, [\pm 45^\circ]_{2s}, [\pm 60^\circ]_{2s}\)

To examine the effect of membrane thickness and support beams’ width and thickness, a comparison of structural properties is drawn based on the total weight of the flapping wing, Table 1. At first, the membrane thickness is increased gradually, fixing the beam thickness and width, and the total weight of the flapping wing is calculated. Then the membrane thickness is kept constant (1 mm), and support beam width and thickness are increased with the same value in such a way that it matches the total weight of the specific case number.

| Case No. | I.   | II.  | III.  | IV.  | V.   |
|----------|------|------|-------|------|------|
| Beam weight | 3.129 g | 3.129 g | 3.129 g | 3.129 g | 3.129 g |
| Total weight of the wing | 56.459 g | 62.853 g | 67.129 g | 72.429 g | 83.129 g |

To understand the influence of beam orientation on the overall structural performance of the flapping wing, apart from the conceptual one, two other support beam systems are designed; namely, bat-wing type and frame type, Figure 2. The total weight difference among the models is within 1%.

3.2 *Meshing and boundary conditions*

To simulate the real behavior of the flapping wing, the FEM model must be accurate. In general, smoothing the mesh would lead to more accurate results, even though it increases the CPU time. Therefore, a mesh convergence study is always appreciated to find the balance between accuracy and computation time [30].

For the present study, both the membrane and the support beams are modeled as shell elements. Commonly, the beam section is modeled as beam elements or solid elements. However, few predicted
results indicate that modeling the beam with shell elements does not affect the outcome. Therefore, to avoid the solid-shell surface connection in Ansys and to accurately define the bonded contact between membrane and beam section, both are modeled as quadrilateral shell elements, Figure 3 (a). Then a mesh convergence study is performed and the element size is determined as 2 mm, Figure 3 (b).

Figure 3. Mesh information of the flapping wing a) Meshed body with shell elements, b) Mesh convergence study.

Figure 4. Boundary conditions of the flapping wing

A complete flapping cycle is divided into 12 segments, and for each segment, the load is calculated on each element, dividing the wing into 32 elements in total. The flapping wing is modeled as cantilever beam (left most vertical beam is fixed), and the calculated load of each component is applied on the wing surface, shown in Figure 4.

4. Numerical Validation

The validation of the present study is checked by comparing the out of plane displacement results of simply supported composite plates under uniformly distributed load available in the literature [24], Table 2. The results agree quite well with each other.

| Laminate Code | Exact Solution Results [24] | Author FE Solution Results [24] | Ansys FE Results |
|--------------|-----------------------------|---------------------------------|-----------------|
| [0°/90°]_T  | 47.8536 mm                  | 47.9044 mm                      | 47.752 mm       |
| [0°/90°/0°/90°]_T | 3.4036 mm                  | 3.429 mm                        | 3.4176 mm       |
| [0°/90°/90°/0°]_T | 5.8166 mm                  | 5.842 mm                        | 5.8322 mm       |
| [45°/-45°/45°/-45°]_T | 2.75844 mm                | 2.76098 mm                      | 2.7639 mm       |
| [15°/-15°/15°/-15°]_T | 6.3881 mm                 | 6.3881 mm                       | 6.424 mm        |
| [45°/-45°]_T  | 40.65524 mm                 | 40.6654 mm                      | 40.67 mm        |
| [15°/-15°]_T  | 66.13906 mm                | 66.1416 mm                      | 67.979 mm       |

5. Results of Parametric Studies

5.1 Effect of the fiber orientation angle

Firstly, equivalent von Mises stress results are checked on each layer of investigated composite laminates for the calculated pressure load, and results are plotted only for the layer which exhibits maximum stress during each segment, Figure 5. For all the laminates, the bottom-most layer which is connected with the support beam, shows maximum equivalent stress; except for the laminate code [90°/0°/45°/-45°], while the second bottom most layer exhibits maximum stress during the whole flapping cycle. It is important to note that, despite the variation in lay-up configuration, the stress curve pattern is similar for all the laminae while the peak maximum stress is found for flapping segment III (60°) during the downstroke events. Besides, for this segment, both the laminates [90°/90°/45°/-45°], and [45°/-45°]_2, experience almost 25% higher stress than [0°/45°/-45°/90°], and [30°/-30°]_2 laminates.
The maximum stress investigation does not represent the overall condition of the composite laminates. Therefore, a Tsai-Wu failure theory is adopted to confirm the first ply failure criterion of the membrane, Figure 6. For instance, even though $[\pm 60^\circ]_2s$ laminate shows less stress distribution than $[90^\circ/0^\circ/45^\circ/-45^\circ]$s and $[\pm 45^\circ]_2s$, however, failure is seen on the top and bottom most layers of the laminate, Figure 7. Apart from that, no other laminates were failed; nonetheless, the top and bottom most layers of $[90^\circ/0^\circ/45^\circ/-45^\circ]$s and $[\pm 45^\circ]_2s$ laminates have critical areas that should be taken into account for flapping wing design.

From Figure 8, it is evident that during a flapping cycle, support beam takes more stress than the laminates. The equivalent von Mises stress found on the support beams of $[\pm 60^\circ]_2s$ and $[\pm 45^\circ]_2s$ laminates are showing invalid results since the material model of aluminum alloy is linear and cannot predict accurate results after the yield criterion. Yet, it can describe the discrepancy of stress limits due to the adoption of the differently configured membrane. Similar trends can be observed for the deflection of the flapping wing tip, Figure 9.

Even though the stress distribution, failure index and deflection of $[0^\circ/45^\circ/-45^\circ/90^\circ]$s laminated flapping wing is satisfactory among all the examined models; however, it fails to meet the general requirements of the engineering design, where it exhibits large deflection at the wing tip, exceeding...
10% of the semi span length of the wing. Further analysis are carried out based on this selected configuration.

5.2. Effect of membrane thickness

The effect of increasing the membrane thickness and the support beam thickness and width is illustrated in Table 3 and 4, respectively, for the quasi-isotropic laminate \([0^\circ/45^\circ/-45^\circ/90^\circ]\), and flapping segment III. Some interesting results are observed here. As it can be seen, increasing the ply thickness gradually (keeping the support beam thickness and width constant) would result in less stress distribution on layer I (bottom most layer), VIII (top most layer) and support beam. However, increasing the width and thickness of the support beam would result in better stiffness of the flapping wing.

| Case No. | Total deformation | Stress at layer I | Stress at layer VIII | Stress on al. beam |
|----------|------------------|------------------|---------------------|-------------------|
| I        | 66 mm            | 176.5 MPa        | 133.5 MPa           | 225.6 MPa         |
| II       | 48.03 mm         | 143.14 MPa       | 108.21 MPa          | 171.65 MPa        |
| III      | 39.5 mm          | 125.84 MPa       | 95.08 MPa           | 145.21 MPa        |
| IV       | 31.428 mm        | 108.24 MPa       | 81.74 MPa           | 119.5 MPa         |
| V        | 20.808 mm        | 82.46 MPa        | 62.21 MPa           | 84.418 MPa        |

| Case No. | Total Deformation | Stress at Layer I | Stress at Layer VIII | Stress on Al. Beam |
|----------|-------------------|------------------|---------------------|-------------------|
| I        | 66 mm             | 176.5 MPa        | 133.5 MPa           | 225.6 MPa         |
| II       | 45.83 mm          | 143.46 MPa       | 122.13 MPa          | 223.17 MPa        |
| III      | 36 mm             | 126 MPa          | 117 MPa             | 203.61 MPa        |
| IV       | 27.2 mm           | 108 MPa          | 116.2 MPa           | 170 MPa           |
| V        | 16.6 mm           | 82.02 MPa        | 96.66 MPa           | 123.12 MPa        |

5.3. Effect of the beam orientation

Support beam plays a vital role in carrying the stress and provides the stiffness of the wing during a flapping cycle. Therefore, support beams are modeled in three different ways without increasing the total weight of the flapping wing, to study the effect of its orientation on the structural properties of the flapping wing, Table 5 (flapping segment III, membrane laminate \([0^\circ/45^\circ/-45^\circ/90^\circ]\)). It can be seen that both the bat-beam model and frame-beam model increase the stiffness of the flapping wing by reducing the wing tip deformation by 16.67% and 25.75%, respectively. However, adoption of the bat-beam model would increase the stress at layer I by 22% and layer VIII by 46%, which would eliminate the preference of using the bat-beam model as support beam system. On the other hand, in comparison with the initial beam model, the frame-beam model reduces the maximum stress at layer I and layer VIII by 35.8% and 17.2%, respectively, and reduces the maximum equivalent stress of the support beam by 7.55%; which makes it a better choice for the design.

| Beam Model      | Total Deformation | Stress at Layer I | Stress at Layer VIII | Stress on Al. Beam |
|-----------------|-------------------|------------------|---------------------|-------------------|
| Initial beam Model | 66 mm             | 176.5 MPa        | 133.5 MPa           | 225.6 MPa         |
| Bat-beam Model  | 55 mm             | 214.25 MPa       | 195.9 MPa           | 245.17 MPa        |
| Frame-beam Model | 49.6 mm           | 113.7 MPa        | 110 MPa             | 208.6 MPa         |
6. Conclusion
Manufacturing a flapping wing air vehicle is challenging due to its tiny structure, accessible material selection, appropriate flight mechanism, and complex aerodynamics model. They are still undergoing crucial developmental stages, where every parameter related to air vehicle modeling is critical. To contribute to the ongoing research, parametric structural modeling is performed on a biomimetic flapping wing made of composite laminate and aluminum alloy support beam, and the following conclusions are derived from the present study.
1. Fiber orientation angle can significantly impact the flapping wing structure from becoming safe to a completely failed one. Among the investigated ply orientation sequences, quasi-isotropic $[0/45/-45/90]$ laminate performs best.
2. Even though the initial flapping wing model, $[0/45/-45/90]$, has passed the failure criterion, however, large tip deflection results may invalidate the model.
3. During a flapping cycle, support beam takes more stress than the membrane of the wing.
4. Increasing the ply thickness would significantly reduce the total deformation and increase the load-carrying capacity of the wing.
5. Increasing the beam thickness and width would consequently increase the stiffness of the model.
6. Support beam structure can play a vital role in combination with the appropriate ply orientation to further improve the overall stiffness and the load-carrying capacity of the wing. Among the three different support beam models, the frame type support beam has exhibited better performance in terms of structural modeling.

In summary, parametric structural modeling has provided an insight into designing the flapping wing and revealed the important parameters to be considered during the primary stages of modeling. In the future, a composite support beam system will be investigated in order to achieve a more reliable flapping wing for micro air vehicles.

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