

Numerical Study on Aerodynamic Performance of the Wrinkled Flexible Dragonfly Forewing in Gliding Flying

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Abstract

Dragonflies are highly skilled flyers in the natural world, capable of performing flight maneuvers such as lateral flight, hovering, and backward flight—many of which are difficult for human aircraft to achieve. The exceptional flight abilities of dragonflies are closely related to their wings. The wrinkled and venous structures on their wings provide aerodynamic advantages that flat wings with equal thickness, equal projected area, and identical shape profiles do not possess. At the same time, dragonfly wings have a certain degree of flexibility, which causes deformation under aerodynamic forces during flight. This deformation, in turn, affects the aerodynamic characteristics of the wings. To reveal the impact of the wing wrinkling and flexibility on the aerodynamic properties, this study established a three-dimensional CFD model and CSD model of the dragonfly's wrinkled forewing based on previous measurements and research results using 3D modeling software. Modal analysis was performed to verify the model's accuracy. Using the CFD method and a CFD/CSD bidirectional fluid-structure coupling calculation method, numerical simulations were conducted on the aerodynamic characteristics of both rigid and flexible wrinkled forewings, as well as flat forewings with equal thickness, equal projected area, and identical shape profiles during gliding flight. The results showed that the stronger leading-edge vortex and the attached vortices within the wrinkled structure improve the aerodynamic performance of the dragonfly's forewings. Additionally, for the wrinkled forewings, the flexibility factor causes the wing veins and membrane to deform under aerodynamic loads. The pressure difference between the upper and lower surfaces of the flexible forewing is reduced compared to the rigid forewing, leading to a decrease in both lift and drag. However, in terms of the final result, the aerodynamic performance of the dragonfly's forewings is enhanced.

Keywords

Dragonfly, Fluid-Structure Interaction, Wrinkles, Flexibility, Aerodynamic Simulation

1. Introduction

Due to their small characteristic length and low flight speed, micro-air vehicles have a very low Reynolds number (Re) during flight. Due to the difficulty in maintaining a laminar boundary layer on the wing surface and the instability of the airflow, micro-air vehicles suffer from drawbacks such as a small stall angle of attack and poor gust resistance [1]-[6]. In contrast, numerous insects in nature can achieve stable and low-energy consumption flight at extremely low Reynolds numbers. For example, the petite dragonfly, with a body length of less than 4 cm, is capable of gliding thousands of kilometers across the Atlantic Ocean [7]. Research has shown that the deformation of flexible wings in insects is one of the primary mechanisms that use to overcome aerodynamic limitations at low Reynolds number [8]-[10]. Therefore, studying the aerodynamic performance of dragonfly wings can provide valuable insights for the design of micro air vehicles.

The deformation of flexible wings during dragonfly flight is a typical fluid-structure interaction (FSI) problem [11]. Currently, there have been several studies on the flexible wings of dragonflies. Hamamoto *et al.* [12] [13] addressed the FSI problem of dragonfly hovering using the finite element analysis method, and their results indicated that the deformation of flexible wings has a minor impact on their aerodynamic characteristics. Meng *et al.* [14] conducted numerical simulations of the deformation of flexible wings during dragonfly flapping flight based on the Computational Fluid Dynamics/Computational Structural Dynamics (CFD/CSD) approach. Their findings revealed that the deformation of flexible wings reduces drag, increases thrust, and enhances the flight performance of dragonflies, however, the model they established is actually a flat plate with the profile of a dragonfly wing. Hao *et al.* [15] developed an FSI solver suitable for analyzing the aerodynamic characteristics of flexible membrane flapping wings using Matlab software, they analyzed the instantaneous and time-averaged aerodynamic responses of rigid and flexible dragonfly wing models during forward flight but neglected important structures such as veins, membranes and wrinkles. The fore mentioned studies considered only the deformation of flexible wings, but wrinkles are one of the most prominent structures on dragonfly wings. Literature [16]-[18] on dragonfly wrinkled wings indicates that compared to flat plates, wrinkled wings have a higher lift-to-drag ratio; however, Rees [19] and Meng *et al.* [20] suggested that the lift-to-drag ratio of wrinkled wings is lower than that of flat plates. The research by Zhang *et al.* [21] shows that the lift-to-drag ratio of the dragonfly's wrinkled wing is lower than that of a flat plate. By altering the amplitude of the corrugations, its aerodynamic performance can be significantly im-

proved, making the lift-to-drag ratio of the wrinkled wing higher than that of the flat plate. However, in actual dragonfly flight, both the corrugations and the deformation of the flexible wings occur simultaneously.

Based on the actual forewings of dragonflies and previous measurement data and research findings, this paper constructs three-dimensional CFD and CSD models of dragonfly forewings with wrinkle structures after appropriate simplification. Using CFD/CSD bidirectional coupling calculation methods, we investigate the aerodynamic characteristics of three-dimensional dragonfly forewings to reveal the effects of wrinkles and flexibility on the aerodynamic performance of forewings during gliding flight.

2. Model and Methodology

Wrinkled structures are a distinctive feature of dragonfly wings, as shown in **Figure 1**. Okamoto *et al.* discovered through multiple observations and experiments that the wings of dragonflies exhibit wrinkled structures along both the spanwise and chordwise sections [22]. The wrinkles on the forewings of dragonflies are actually significant structures formed by the spatial distribution of veins and membranes. They are primarily characterized by the concave down and convex up shapes of the wing membranes, with the veins located at the bottom end of the concave regions or at the peaks of the convex regions.

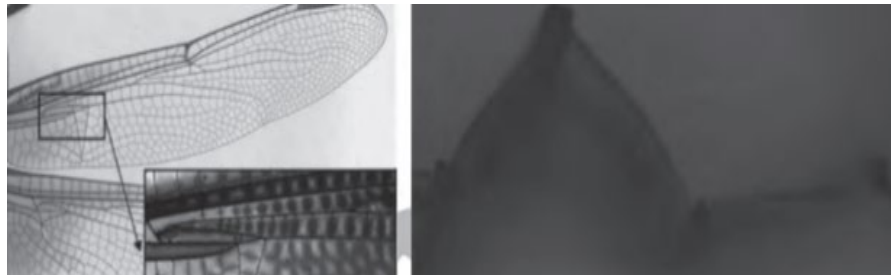


Figure 1. Wrinkles of dragonfly wings.

2.1. Simplification and Establishment of the Geometric Model

To reduce the difficulty of modeling, the following simplifications were made to the forewings of dragonflies based on existing studies [23] [24]: 1) The size variations of veins and membranes along both the spanwise and chordwise directions of the forewings are ignored, and the average sizes of veins and membranes are used; 2) The effects of extremely small wrinkles as well as the internal structures within the wrinkles are neglected. Minor changes in the shape of veins are also disregarded, and the shape of veins on the forewings of dragonflies is simplified to circular tubes with a diameter of 0.18 mm, while the thickness of the wing membrane is 4 μm ; 3) The material properties (Young's modulus, Poisson's ratio, etc.) of veins and membranes along both the spanwise and chordwise directions are ignored. According to the literature [25], the parameters in **Table 1** [25] are adopted in this paper (where there are two thickness values for the three-dimen-

sional wrinkled forewings of dragonflies: 0.18 mm for the diameter of the circular tube-like veins and 0.004 mm for the thickness of the wing membrane); 4) The influence of the dragonfly’s body and hindwings on the aerodynamic characteristics of the wrinkled forewings is ignored.

Table 1. Model parameters.

	Average chord length <i>c</i> /mm	Wingspan <i>l</i> /mm	Thickness δ /mm	Reference area <i>S</i> /mm ²
Wrinkled forewing	8	40	0.18, 0.004	284.1
Flat forewing	8	40	0.18	284.1

As shown in **Figure 2** and **Figure 3**, the final CFD model and CSD model of the three-dimensional wrinkled forewings of dragonflies are established [25].

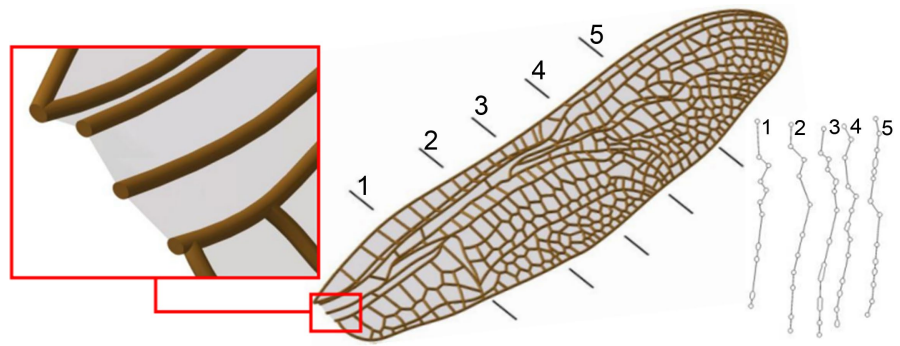


Figure 2. CFD model.

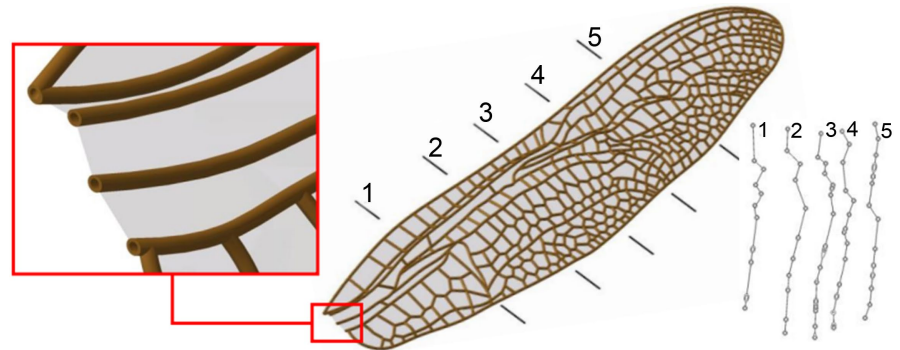


Figure 3. CSD model.

2.2. Computational Method and Governing Equations

Fluid Governing Equations:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \tag{2}$$

$$\frac{\partial v}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{R_e} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (3)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{R_e} \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (4)$$

In the equation, u , v , w represent the components of velocity in the x , y , z directions in the coordinate system, e , p , t , R_e represent the pressure, time, and Reynolds number, respectively.

Solid Governing Equations:

$$\rho_s \cdot \mathbf{d}_s = \nabla \cdot \sigma_s + F_s \quad (5)$$

In the equation, ρ_s and \mathbf{d}_s respectively represent the density of the solid and the Cauchy stress tensor; σ_s and F_s respectively represent the local acceleration vector and the body force vector of the solid.

Fluid-Solid Coupling Equations:

$$\tau_F \cdot n_F = \tau_s \cdot n_s \quad (6)$$

$$d_F = d_s \quad (7)$$

In the equation, τ_F and τ_s respectively represent the stress values in the fluid domain and the solid domain; n_F and n_s respectively represent the normal unit vectors of the contact surfaces in the fluid domain and the solid domain; d_F and d_s respectively represent the displacement vectors generated by the fluid elements and the solid elements.

Turbulence Model: SST k- ϵ turbulence model.

2.3. Computational Grid

The computations in this paper utilize the finite element analysis software Siemens-starccm+. Both the CFD and CSD grids refer to the grids previously generated by Luo *et al.* [26] in the starccm+ software. The grid conditions are shown in **Figures 4-7**.



Figure 4. Fluid grid of the flat forewing.



Figure 5. Solid grid of the flat forewing.

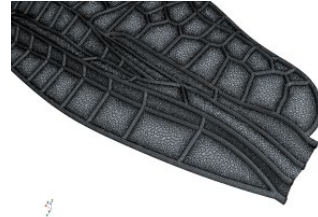


Figure 6. Fluid grid of the wrinkled forewing.



Figure 7. Solid grid of the wrinkled forewing.

2.4. Model Parameters

Referencing the setup by Yu *et al.* [27], the parameters are as follows (**Table 2** and **Table 3**):

Table 2. Aerodynamic parameters.

Density	Dynamic viscosity	Resultant velocity	Characteristic length	Reynolds number (Re)
1.18415 kg/m ³	1.85508E-5 Pa·s	5 m/s	8 mm	2553.31

Table 3. Solid parameters.

Density	Poisson's ratio	Young's modulus
1200 kg/m ³	0.25	17.0 GPa

3. Results and Discussion

To reveal the aerodynamic effects of corrugation and flexibility on the dragonfly's forewing during gliding, the following cases were calculated: 1) rigid flat plate forewing, 2) flexible flat plate forewing, 3) rigid wrinkled forewing, 4) flexible wrinkled forewing, with the angle of attack ranging from 0° to 25° (with a 5° increment). The aerodynamic parameters of the forewing during gliding were calculated for these four cases. The differences in aerodynamic characteristics of the four forewings at different angles of attack during gliding were mainly determined based on the lift coefficient (*c_l*), drag coefficient (*c_d*), and lift-to-drag ratio (*c_l/c_d*) [28].

3.1. Comparison of Aerodynamic Characteristics between Rigid Flat Forewing and Rigid Wrinkled Forewings during Gliding

Within the attack angle range of 0° - 25°, compared with the rigid flat forewing,

the wrinkles significantly increase the lift coefficient of the forewing, and also increase the drag coefficient, however, the increase amplitude is extremely small relative to the lift coefficient. This result also makes the lift-to-drag ratio of the wrinkled forewing significantly improved compared to the flat forewing, as shown in **Figure 8**.

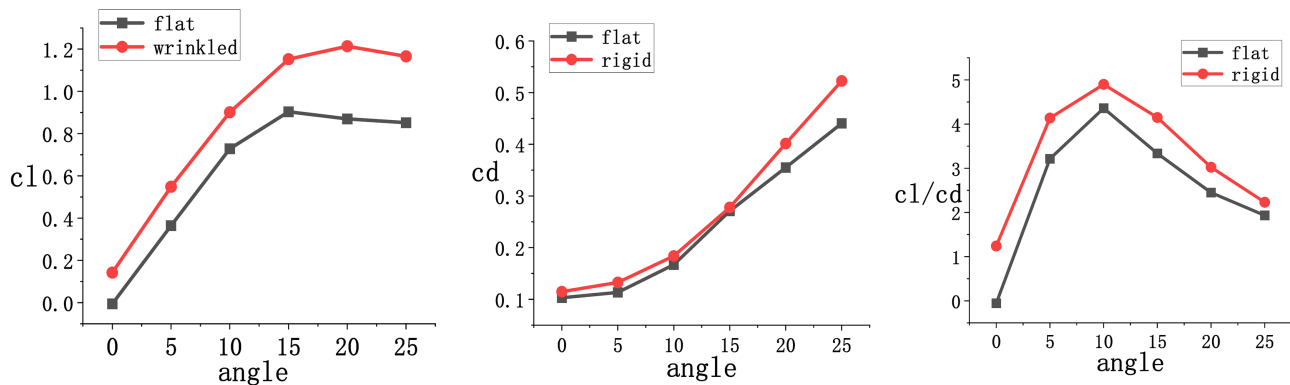


Figure 8. Aerodynamic characteristics of rigid flat and wrinkled forewing.

The lift coefficient of the flat plate forewing at 0° angle of attack is zero, but the lift coefficient of the wrinkled forewing at 0° angle of attack is greater than zero. The main reason for this is that the wrinkled structure of the forewing attaches a stationary vortex, making its flow similar to that of a smooth airfoil. The corrugations introduce some curvature to the dragonfly's forewing, and at 0° angle of attack, the forewing behaves like a smooth asymmetric airfoil. Therefore, even with a 0° angle of attack, the wrinkled forewing still generates some lift, while the flat plate forewing, which behaves like a symmetric airfoil, cannot produce lift at 0° angle of attack, as shown in **Figure 9(a)** and **Figure 9(b)**. When the attack angle is not zero, there are leading-edge vortices at the leading edge of both the wrinkled forewing and the flat forewing, as shown in **Figure 9(c)-(f)**. The leading-edge vortices of the wrinkled forewing are stronger than those of the flat forewing, especially at the middle position along the span of the forewing. Since the leading vein of the wrinkled forewing is the same size as the leading edge of the flat forewing, and the shape of the leading edge of the flat forewing is semicircular, consistent with the shape of the vein, the presence of the wrinkles induces leading-edge vortices with different structures and strengths. Therefore, the stronger leading-edge vortices and the attached resident vortices in the wrinkle structure are important reasons why the wrinkled forewing has better aerodynamic performance than the flat forewing. For convenience in displaying the vorticity and pressure distribution, the following presents the vorticity isosurface with the Q criterion function of $1.0E-7/s^2$ added with the velocity nephogram, as well as the pressure distribution nephogram on the wing surface.

The above results are consistent with those of Liu [25].

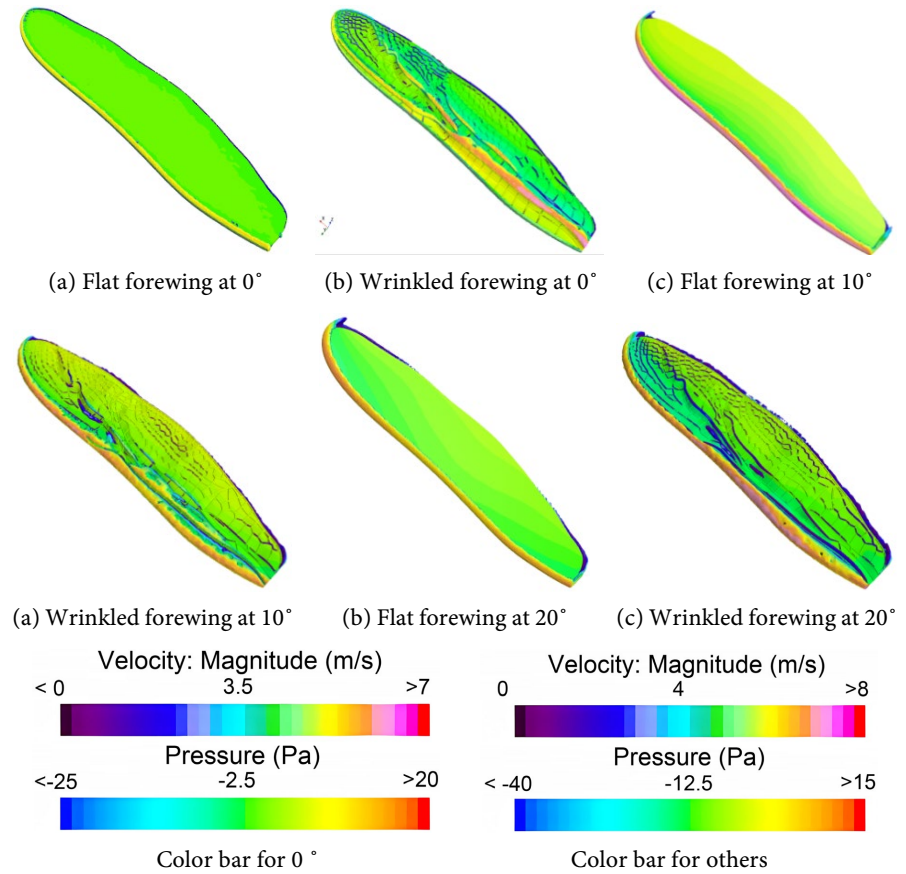


Figure 9. Speed and pressure nephogram.

3.2. Comparison of Aerodynamic Characteristics of Flexible Flat Plate Forewing and Flexible Wrinkled Forewings during Gliding

Within the range of 0° to 25° angle of attack, the flexible wrinkled forewing still exhibits superior aerodynamic characteristics compared to the flexible flat plate forewing, even outperforming the rigid wrinkled forewing relative to the rigid flat plate forewing. This advantage is mainly reflected in the percentage increase in lift-to-drag ratio at the angle of attack where the maximum lift-to-drag ratio occurs (10°). The increase for the rigid case is 12%, while for the flexible case, it is 28%. The aerodynamic parameters of the flexible flat plate forewing and the flexible wrinkled forewing are shown in **Table 4**. The mechanism behind this aerodynamic advantage is similar to the one described in **Section 3.1**. This section’s calculation is included to demonstrate that, regardless of whether under flexible or rigid conditions, the corrugations contribute similarly to the aerodynamic performance of the dragonfly’s forewing. The inclusion of flexibility does indeed cause changes in lift and drag, and these effects will be explained in **Section 3.3**, so they are not elaborated on here.

3.3. Comparison of Aerodynamic Characteristics of Rigid Wrinkled Forewing and Flexible Wrinkled Forewings during Gliding

Within the range of 0° to 25° angle of attack, both the lift and drag of the flexible

wrinkled forewing are greater than those of the rigid wrinkled forewing, as shown in **Figure 10**. However, under the experimental conditions, it can be considered that the aerodynamic characteristics of the flexible wrinkled forewing are slightly superior to those of the rigid wrinkled forewing. This is mainly reflected in the lift-to-drag ratio, especially around the angle of attack where the maximum lift-to-drag ratio occurs (approximately 10°), as shown in **Figure 10**.

Table 4. The aerodynamic parameters of the flexible flat plate forewing and the flexible wrinkled forewing.

angle/ $^\circ$	cl		cd		cl/cd	
	flat	wrinkled	flat	wrinkled	flat	wrinkled
0	0.0008568	0.1199	0.1024	0.1012	0.008365	1.186
5	0.3641	0.5036	0.1181	0.1206	3.083	4.175
10	0.7185	0.8588	0.1827	0.1702	3.932	5.046
15	0.8348	1.110	0.2746	0.2580	3.040	4.303
20	0.7971	1.095	0.3484	0.3566	2.288	3.071
25	0.7771	1.005	0.4224	0.4478	1.840	2.245

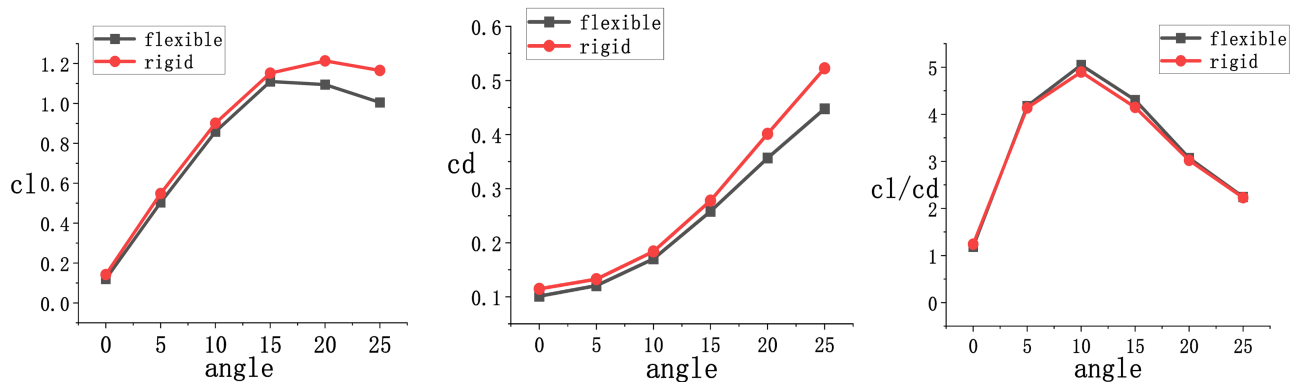


Figure 10. Aerodynamic characteristics of flexible and rigid wrinkled forewing.

Comparing the pressure nephogram of the rigid and flexible wrinkled forewings, the surface of the flexible forewing membrane becomes uneven due to the aerodynamic forces. The low-pressure regions on the upper surface exhibit relatively higher pressure distribution, while the high-pressure regions on the lower surface show relatively lower pressure distribution, as shown in **Figure 11**. The pressure difference between the upper and lower surfaces of the membrane is reduced compared to that of the rigid forewing. A smaller pressure difference means that the resultant force on the wing is smaller, and one component of this resultant force-drag-is also smaller. Therefore, the drag coefficient of the flexible forewing is lower than that of the rigid forewing. Additionally, the reduction in drag coefficient at large angles of attack (e.g., 25° , with a reduction of 0.075) is greater than

at small angles of attack (e.g., 5°, with a reduction of 0.012). This result is consistent with Liu’s findings [28].

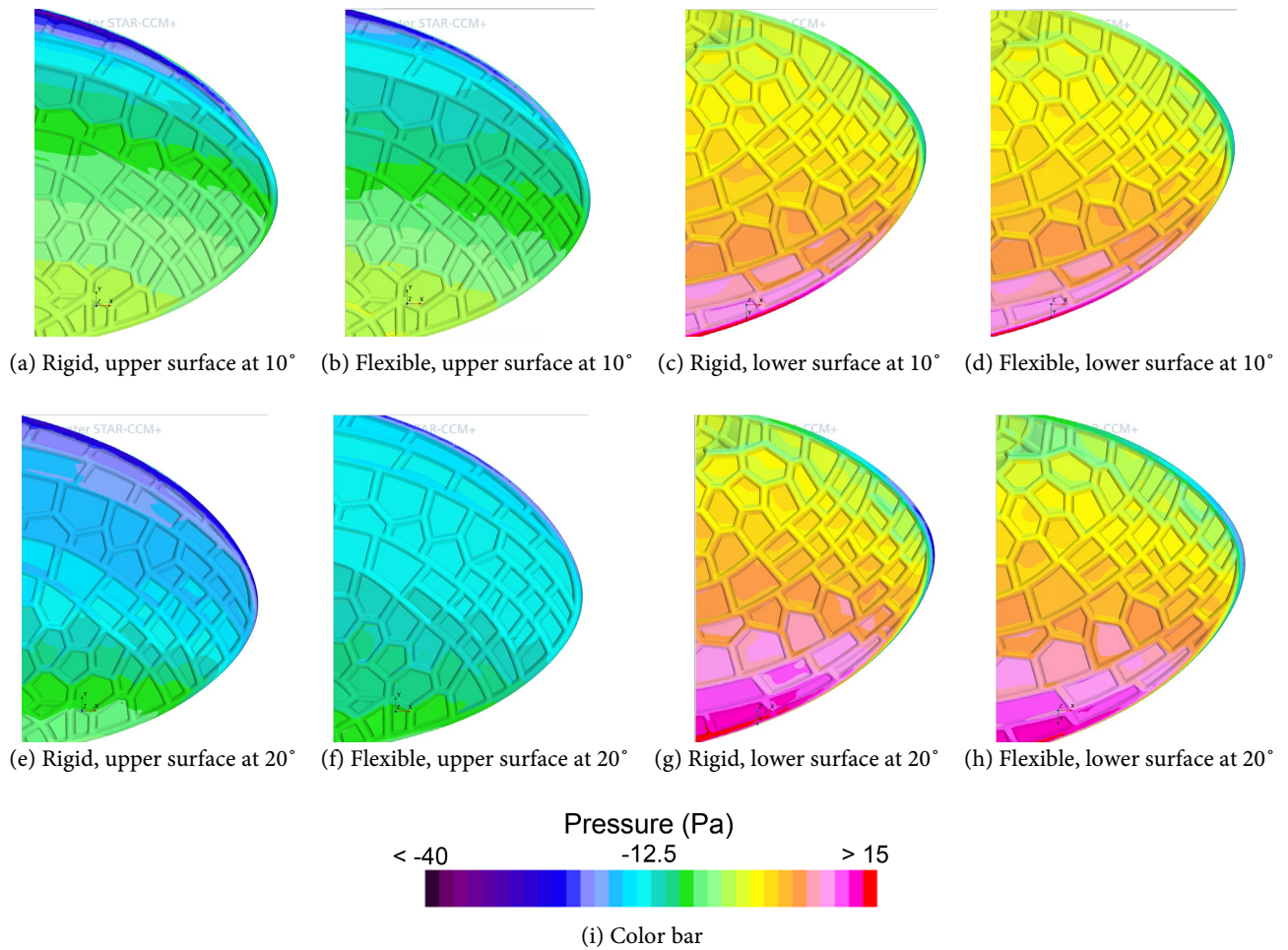


Figure 11. Pressure nephogram.

The pressure difference between the upper and lower surfaces of the flexible forewing membrane is lower compared to the rigid forewing membrane. A lower pressure difference means the resultant force on the wing is smaller, and one component of this force-lift is also smaller. Numerical simulations also show that, within the 0° to 25° angle of attack range, the lift coefficient of the flexible forewing is smaller than that of the rigid forewing. This differs from Liu’s results [28], and this paper suggests that the discrepancy is due to the difference in Young’s modulus used in the CSD model, which causes different induced vortices at the leading edge of the flexible forewing.

3.4. Deformation Analysis of Flexible Forewing

Based on the CFD/CSD bi-directional fluid-structure coupling method, numerical simulations were performed to solve the deformation of the forewing under aerodynamic loading in the flow field during dragonfly gliding at angles of attack

from 0° to 25° (with a 5° interval). The maximum deformation values of the dragonfly's flexible wrinkled forewing at angles of attack from 0° to 25° are as follows: 0.02975 mm, 0.2494 mm, 0.4606 mm, 0.6127 mm, 0.6063 mm, and 0.5940 mm. It can be observed that the trend in the maximum deformation values matches the trend in lift variation.

As shown in **Figure 12**, at an angle of attack of 0° , the maximum deformation of the dragonfly's flexible wrinkled forewing occurs near the rear edge of the wingtip. However, at angles of attack from 5° to 25° , the maximum deformation is located at the wingtip. The flexibility only increases the deformation in the direction perpendicular to the dragonfly's forewing plane, but does not cause torsion of the forewing. That is, the flexibility has little effect on the angle of attack of the dragonfly's wrinkled forewing.

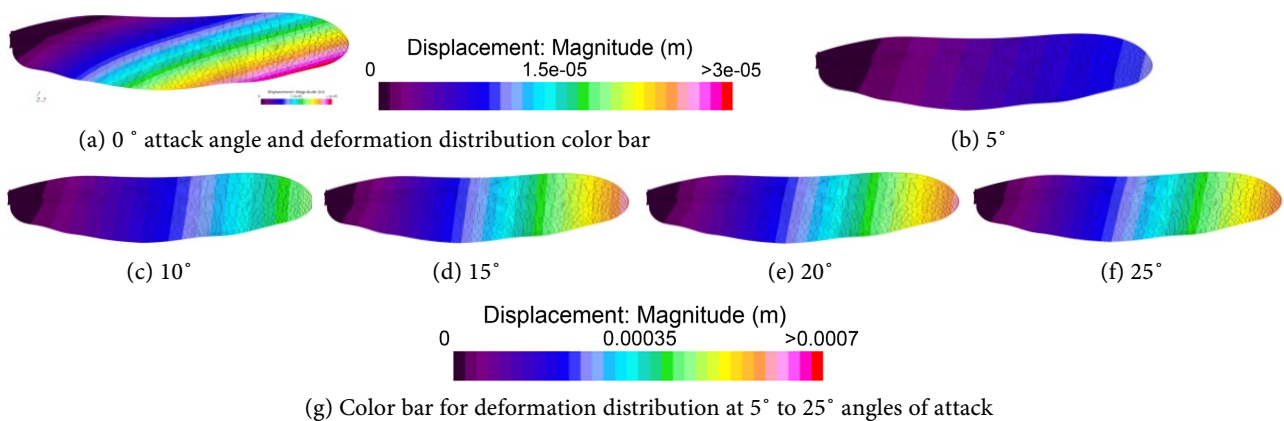


Figure 12. Displacement nephogram.

4. Conclusions

During gliding flight, the wrinkles and flexibility of the dragonfly's forewings both contribute positively to the aerodynamic characteristics of the forewings. The stronger leading-edge vortices caused by the wrinkles and the attached vortex structures within the wrinkles effectively improve the aerodynamic performance of the dragonfly's forewings. At the same time, the flexibility allows the forewings to deform under aerodynamic loads, with the wing veins and membrane undergoing shape changes. As a result, the pressure difference between the upper and lower surfaces of the wing is reduced compared to the rigid forewing, leading to a reduction in both lift and drag. However, in terms of the lift-to-drag ratio, the flexible factor enhances the aerodynamic performance of the dragonfly's forewings during gliding.

During flapping flight, the dragonfly's wing experiences large and frequent changes in angle of attack. The aerodynamic characteristics of the dragonfly's flexible wings are also influenced by these variations in angle of attack. Therefore, flexibility is a characteristic that cannot be overlooked during the dragonfly's flapping flight. Additionally, in cases of drastic changes in angle of attack, the vortices induced by the wrinkles, such as leading-edge vortices and attached vortices,

should not be ignored.

In conclusion, this study helps to explain the exceptional functional performance of dragonfly wings and provides valuable insights for the design of flexible wings in biomimetic flapping-wing aircraft.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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