Numerical Investigation of the Aerodynamic and Structural Characteristics of a Corrugated Airfoil

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Previous experimental studies on static, bioinspired corrugated wings have shown that they produce favorable aerodynamic properties such as delayed stall compared with streamlined wings and flat plates at high Reynolds numbers ($Re \geq 10^5$). The majority of studies have been carried out with scaled models of dragonfly forewings from the Aeshna cyanea in either wind tunnels or water channels. In this paper, the aerodynamics of a corrugated airfoil was investigated using computational fluid dynamics at low Reynolds numbers of 500, 1000, and 2000. A structural analysis was also performed using the commercial software SolidWorks 2009. The complex vortex structures that formed in the corrugated airfoil valleys and around the corrugated airfoil are studied in detail. Comparisons are made with experimental measurements at different Reynolds numbers and with simulations of a flat plate. The study shows that, at low Reynolds numbers, the corrugation does not provide any aerodynamic benefit compared with a flat plate. Instead, the corrugated airfoil generates more drag than the flat plate. Structural analysis shows that the wing corrugation can increase the resistance to bending moments on the wing structure with reduced thickness and weight.

Nomenclature

\begin{align*}
c &= \text{chord} \\
C_D &= \text{coefficient of drag} \\
C_L &= \text{coefficient of lift} \\
D &= \text{drag} \\
f &= \text{wake vortex shedding frequency} \\
L &= \text{lift} \\
P &= \text{pressure} \\
Re &= \text{Reynold's number, } \rho U_\infty c / \mu \\
St &= \text{Strouhal number, } (f c / U_\infty) \sin \alpha \\
\alpha &= \text{angle of attack} \\
\mu &= \text{viscosity} \\
\rho &= \text{density}
\end{align*}

I. Introduction

Micro air vehicles (MAVs) are small aerial vehicles with a typical wingspan of less than 15 cm, and they weigh less than 90 g. Their flight speed usually ranges between 2 to 10 m/s. The development of MAVs is of great interest to both military and civilian applications. MAVs can be used in various scenarios such as reconnaissance, surveillance, targeting, search and rescue, and biochemical sensing in confined or otherwise hazardous conditions. Their applications are very similar to their larger cousin, the unmanned aerial vehicle (UAV), but MAVs have much smaller sizes and much lower costs. As an example, General Atomics Aeronautical Systems, Inc.’s, Predator\textsuperscript{1} MAVs have a cruise speed of about 35 m/s, a wingspan of 14.8 m, and a cost upward of $10 million. The goal of MAV design is to fit the capabilities of a UAV into a far smaller aircraft. While there is vast potential for the use of MAVs, there are several challenges that must be overcome.

Because of the MAV’s slow flight speed, the chord Reynolds number across the wing is low: $10^2$–$10^3$. At such a low Reynolds number, the flow across the wing is typically laminar. Current MAV designs rely on conventional streamlined airfoils for lift generation. However, conventional airfoils are designed to operate at much higher Reynolds numbers, greater than $10^5$. The performance of smooth airfoils greatly deteriorates once the Reynolds number drops below $10^5$. A reproduction of McMasters and Henderson’s maximum lift-to-drag ratio of airfoils through various Reynolds numbers is shown in Fig. 1. The lift-to-drag ratio is the measurement of the effectiveness of an airfoil that is proportional to the gliding ratio and climbing ability of the airfoil [2]. For large aircraft, the boundary layers usually transition to turbulent flow before separation. The turbulent flow can stay attached through more severe pressure gradients. As the Reynolds number falls below $10^5$, flow approaches the adverse pressure region as laminar flow. Since laminar flow cannot resist strong adverse pressure gradient, flow separates as laminar flow. Laminar flow separation typically leads to premature stall, dramatic decrease in the lift, and increase in the drag [2]. To mediate the effects of stalling conditions and the resulting poor lift-to-drag ratio at the low-Reynolds-number region, new airfoil designs must be created.

Dragonflies are known for their exceptional flying performance and their gliding ability. Dragonflies are highly maneuverable: they can fly forward and backward, and they can hover for a long period of time. These characteristics are very desirable for MAV designs. The dragonfly genus Aeshna is capable of gliding for durations up to 30 s without an appreciable loss in altitude [3]. Gliding flight, which requires no energy expenditure, would prove to be a major advantage to MAVs in a power-saving technique [4]. Their superior gliding performance can be attributed to their high-aspect-ratio wings. Ennos [5] and Torres [6] both demonstrated the importance of aspect ratio in gliding flight. Ennos [5] concluded that, as the aspect ratio increases, the gliding ratio will also increase until the profile drag becomes greater than the induced drag. Torres [6] demonstrated the importance of the aspect ratio and planform design to achieve the maximum gliding ratio.

Dragonflies have some of the highest aspect ratio wings in the insect world, which contribute to their gliding performance. The Aeshna juncea (hawkster dragonfly) was calculated to have an aspect ratio...
**Fig. 1** Airfoil performance as a function of chord Reynolds number \([1,2]\).
equations are discretized in space with second-order-accurate central differences onto a set of overlapping grids. The second-order Crank–Nicolson scheme is used for time integration. The PETSc package is used to solve the system of equations. For the Reynolds numbers studied, the flow was assumed to be laminar with no turbulence model employed.

III. Computation Setup

Figure 2 shows the two profiles being tested: a flat plate and a corrugated airfoil. The profile of the corrugated airfoil was taken from the forewing of an *Aeshna cyanea* dragonfly. The original profile was developed by Kesel [13] and then taken by Murphy and Hu [14], who gave a thickness to the airfoil. The flat plate has round leading and trailing edges. The flat plate and corrugate airfoil have the same chord length and thickness of 2% of the chord.

A. Overlapping Grids

An overlapping grid method was used to develop the computational domain. The method employs the use of Cartesian grids as a background grid and structured body-fitted grids around the components of the domain. This allows for the computational domain and its components to be modeled individually with multiple sets of grids for accurate representation of the entire domain. An interpolation region is created between the overlap of the grids to allow information to pass between them. More information can be found in [18].

B. Grid Sensitivity Analysis

The grid sensitivity analysis would systematically vary the number of grid points in the grid domain to investigate the effects of grid density on the aerodynamic forces acting on the airfoil. A Cartesian grid was used as a background grid, and a body-fitting grid was used around the airfoil. The background and airfoil grid were systematically varied to see the changes on the coefficient of lift and drag. The simulations were run until steady or periodic flow patterns developed, ensuring a convergence criteria of $10^{-6}$ was met by the pressure solver for every time step. The time-averaged coefficient of lift and coefficient of drag were then examined.

The coefficients of lift and drag were calculated from the force history of each simulation. The coefficients of lift and drag were computed with Eqs. (3) and (4):

$$c_L = \frac{L}{1/2 \rho U^2 \infty c}$$  \hspace{1cm} (3)

$$c_D = \frac{D}{1/2 \rho U^2 \infty c}$$  \hspace{1cm} (4)

At high angles of attack, periodic vortex shedding was observed in the study. When that occurred, a time-averaged lift and drag were used in Eqs. (3) and (4).

In a recent study, Granlund et al. [19] showed the effects small domain sizes have on the coefficient of lift in water channels. They found the coefficient of lift increased by a factor of 2 when the domain was halved in size. This effect, however, was not prominent until high angles of attack. To mitigate this effect, the top and bottom walls of the computational domain were set to inflow boundaries, and two domain sizes were tested.

At 20 deg, the corrugated profile was tested with 10c × 10c and 20c × 20c domains. The time-averaged coefficients of lift for both cases were 0.948 and 0.952, respectively. The time-averaged coefficients of drag were 0.441 and 0.439, respectively. The relatively small difference in the force coefficients show that any static blockage effect in the computational domain was minimal, thus allowing for a smaller 10c × 10c domain to be used.

The grid sensitivity analysis for the corrugated profile was performed at an angle of attack of 8 deg. The convergence of lift and drag is reported in Table 1. At this angle of attack, no vortex shedding was observed. It seemed that a grid with 600 lines in the circumferential direction and 200 lines in the radial direction (600 × 200) was required. Upon examining the flowfield, it was observed that the wake velocity was quickly damped out as it passed into coarser grids in the wake region. It was determined that an additional grid in the wake region would be required to capture any vortex structures generated at higher angles of attack. Figures 3a and 3b show the old overlapping grid scheme and the new grid scheme (with added grid in the wake region) with respective velocity contours. It was clear that the added trailing-edge grid better resolved the flow structure in the wake. This additional trailing grid reduced the overall sensitivity of the grid to changes in grid density. Thus, the requirement on the airfoil grid could be reduced with the addition of the trailing-edge grid. From the grid sensitivity analysis, it was found a 400 × 100 airfoil grid and a 200 × 100 trailing-edge grid would accurately recreate the necessary grid scheme to produce valid results and preserve the flowfield. The grid spacing along the surface of the corrugated profile was approximately 0.0014c. Without the trailing-edge grid, it would require a 600 × 200 airfoil grid. The same process was performed on the flat plate as the corrugated airfoil. It was found that a grid with a 300 × 100 body-fitted grid with a 200 × 50 trailing grid was sufficient. The grid spacing along the flat plate was 0.0025c.

C. Suitability of a Two-Dimensional Simulation

Given the complex corrugated nature of a dragonfly wing, it is reasonable to question the suitability of a 2-D study. The varying spanwise corrugation would, in theory, induce complex 3-D flow phenomena that could influence the lift and drag generation of the corrugated profile. A 3-D periodic spanwise grid was generated to study the 3-D effects of the corrugation. The wing’s aspect ratio was equal to 1, and the angle of attack was varied from 0 to 12 deg. The time-averaged coefficient of the lift and drag were compared with the 2-D cases. It was found that, for all cases, the lift and drag varied only by a maximum of 8%. Upon further investigation, it was found the effect of the force coefficients resulted from a variation in grid generation, and there was no velocity parallel to the span of the wing. Thus, it was concluded that the 2-D simulation was sufficient.

IV. Results

A. Effect of Angle of Attack

The effect of angle of attack on aerodynamic forces was investigated. The chord Reynolds number remained 1000. For comparison, the calculated coefficients of lift were plotted against experimental data from Kesel [13] at a Reynolds number equal to 10,000 and numerical data from Kim et al. [15] at a Reynolds number equal to 1400, in Fig. 4a. Since vortex shedding occurred at modest angles of attack, the results plotted are the time-averaged coefficient

<table>
<thead>
<tr>
<th>Airfoil grid</th>
<th>Background $C_L$</th>
<th>$C_D$</th>
<th>$C_L$</th>
<th>$C_D$</th>
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<tr>
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<td>0.447</td>
<td>0.192</td>
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<tr>
<td>300 × 100</td>
<td>$160 \times 160$</td>
<td>0.465</td>
<td>0.176</td>
<td>0.607</td>
</tr>
<tr>
<td>400 × 100</td>
<td>$160 \times 160$</td>
<td>0.469</td>
<td>0.181</td>
<td>0.588</td>
</tr>
<tr>
<td>500 × 100</td>
<td>$160 \times 160$</td>
<td>0.472</td>
<td>0.179</td>
<td>0.586</td>
</tr>
</tbody>
</table>

Table 1 Grid sensitivity analysis of corrugated profile and flat plate with trailing grid at a Reynolds number of 1000


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Footnotes:

of lift and drag. The numerical prediction was very close to the experimental data at low angles of attack ($\alpha = 4$ deg). Because of the disparity of Reynolds number used, the closeness seems to indicate the lift was not sensitive to the Reynolds number at low angles of attack. At modest angles of attack, there is a disagreement between Kim et al.'s data and the numerical data. The numerical simulation predicts a lower lift coefficient than the experimental data of Kesel [13] at a high Reynolds number and with Kim et al.'s [15] measurement. The deviation from Kim et al.'s simulation may be explained by the corrugate profile they used. While their profile was identical, the profile thickness was much thinner. As previously stated, Sunada et al. [16] noted that thinner profiled airfoils achieve higher lift. One reason for the high lift in both the numerical simulation and Kim et al.'s [15] data is, at a low Reynolds number, viscosity plays an important role and flow remains attached. Thus, no obvious stall was observed over the range studied.

Comparing the predicted numerical drag coefficient (Fig. 4b) to Kim et al.'s [15] numerical and Kesel's [13] experimental results, it was seen that the predicted numerical drag matches closely with Kim et al.'s [15] results. Again, the numerical data show a deviation from with a higher predicted drag. This can be attributed to a more prominent viscous effect at lower Reynolds numbers. Comparison with the flat plate is shown in Figs. 4c and 4d. The corrugated airfoil and the flat plate produce very similar lift at almost all the angles of attack, which was consistent with Kesel's [13] findings. The corrugated profile produced slightly higher drag than the flat plate,

![Fig. 3 U velocity component contour a) without a trailing grid, and b) with a trailing grid.](image)

![Fig. 4 Numerical results of corrugated profile plotted against published data (Figs. 4a and 4b) and numerical results of the flat plate at a Re of 1000 (Figs. 4c and 4d).](image)
reducing its gliding ratio as seen in Fig. 4d. The corner seen in the lift of the flat plate between angles of 10 and 12 deg cannot be attributed to a hysteresis in the simulation. Each simulation was conducted with a static angle of attack. This corner does not appear in the drag due to viscous forces mainly contributing to the drag as opposed to pressure forces that mainly contribute to lift at this low angle of attack.

B. Effect of Reynolds Number

The effect of the Reynolds number was also investigated. The results of the Reynolds numbers of 500 and 2000 were compared with the previous results. As previously discussed, Wakeling and Ellington [8] showed that dragonflies glide predominately at low angles of attack. Thus, for the cases for the Reynolds numbers of 500 and 2000, the angle of attack was only varied from 0 to 20 deg. The results of the force coefficients for the corrugated airfoil are shown in Fig. 5a. At low angles of attack, \( \alpha \leq 12 \) deg, lift remained relatively unchanged. At higher angles, \( \alpha > 12 \) deg, lift grew with the Reynolds number. As the Reynolds number increases, viscous effects become less prominent, and drag decreases. The decrease in drag increases the gliding ratio, as seen in Fig. 5b.

Similar results were seen with the flat plate. The results of the force coefficients are shown in Fig. 6a. As the Reynolds number increased, the lift remained constant for low angles of attack, \( \alpha \leq 12 \) deg. At higher angles, lift increased with the Reynolds number. Like the corrugated profile, drag decreased with an increasing Reynolds number due to the lessening of viscous forces. Unlike the corrugated profile, the reduction of drag led to a large growth in the gliding ratio; see Fig. 6b.

C. Effects of Leading Edge

Observing the stark differences in gliding ratios between the corrugated profile and flat plate at the various Reynolds numbers, it was plausible to assume the differences in the leading- and trailing-edge geometries of both profiles may have played a part. To analyze the effect the leading- and trailing-edge geometries had on the force coefficients, a rounded edge flat plate was compared with a flat plate with squared edges. Both flat plates were simulated at Reynolds numbers of 500, 1000, and 2000, with the angle of attack being varied from 0 to 20 deg.

In Figs. 7a and 7b, there was little difference observed between the two edge types in terms of the force coefficients at Reynolds numbers of 500 and 1000. When the Reynolds number was equal to 2000 (Fig. 7c), the differences between the lift and drag of the two profiles were beginning to diverge. The square edge was producing 3% more lift and drag on average compared with the rounded edge. It was concluded that the edge geometry had little impact at these low Reynolds numbers. Kunz [20] came to a similar conclusion; it was found when the Reynolds number was less than 6000 and the edge geometry was not a dominating factor in force production.

D. Effects of Corrugation

Examining the streamlines around the corrugated airfoil, at a Reynolds number of 1000, it was found that near-stagnant rotating flow was trapped within the valleys of the corrugation. Because of the trapped vortices, the corrugated airfoil acted like a thick smooth airfoil. This is similar to what was seen in [4,11,12,14]. For visual aid, the virtual profile was outlined in Fig. 8. The illustration shows...
the virtual profile around the corrugation compared with the flat plate at various angles of attack. The virtual profile was drawn through visual inspection of where the velocity near the airfoil became greater than 0.1\(U_\infty\). As the angle increased, the increase in virtual profile thickness of the corrugated airfoil increased the pressure drag. The flat plate does not show a virtual profile thickness until approximately 8 deg. When the angle is less than 8 deg, the flow sticks to the surface of the flat plate, increasing viscous drag, yet pressure drag is reduced. Flow across the corrugated profile conveys across the slowly rotating flow in the valleys, which results in the formation of the virtual profile. The rotating flow in the valleys results in the production of negative viscous drag that reduces the total drag caused by shear. Because of the large separation of flow across the corrugated profile, there is a large increase in pressure drag compared with the flat plate.

At 8 deg, the coefficient of drag for the corrugated airfoil and the flat plate were 0.156 and 0.141, respectively. The viscous drag made up only 17% of the total drag on the corrugated airfoil, while the viscous drag made up 30% of the drag on the flat plate. This effectively shows that the corrugated airfoil can lower viscous drag. However, because of the thick virtual profile produced by the trapped vortices, the pressure drag on the corrugated airfoil was 1.34 times higher than the flat plate's pressure drag. This increase in drag reduces the lift-to-drag ratio. Both the flat plate and the corrugated airfoil produced peak lift-to-drag ratios (\(C_L/C_D\)) of around 6 deg. The peak lift-to-drag ratio of the flat plate and the corrugated airfoil were 4.3 and 3.3, respectively.

E. Stability of the Corrugated Airfoil

At angles greater than 12 deg, both the corrugated profile and the flat plate began to exhibit vortex shedding. The vortex shedding causes both lift and drag to oscillate on the airfoils. The Strouhal number of the vortex shedding at different angles of attack is plotted in Fig. 9a, which was found using Eq. (5):

\[
St = \sin \alpha \frac{f_c}{U_\infty} \tag{5}
\]

Overall, the Strouhal number remains constant as the angle of attack increases, which is consistent with the observation that the Strouhal number over a blunt body is approximately 0.2. The corrugated profile and the flat plate demonstrate similar vortex shedding patterns at high angles of attack, indicating both of them behave like a blunt body. Figure 9b plots the maximum and minimum lift at each angle of attack for the corrugated profile and flat plate. Comparing Figs. 9a and 9b, it can be seen again how the corrugated profile acts very similar to the flat plate, even in lift oscillation. The lift history shown in Fig. 10 illustrates the similarities of the shedding frequency and lift oscillations in both the flat plate and corrugated airfoil at 20 deg. In Fig. 11, snapshots are shown of the vorticity contours of both airfoils at 20 deg. The snapshots were taken at the time instants corresponding to maximum and minimum lift. It is important to note that the corrugation does not seem to affect the shedding frequency.

F. Viability of Corrugated Airfoil

The numerical simulations have demonstrated that the corrugated airfoil acts similar in lift production as a flat plate; however, it produces more drag, which agrees with Kesel [13]. This increase in drag is because the near-stagnate rotating vortices make the corrugated airfoil function like a thick streamlined airfoil. Because of its high pressure drag, the corrugated airfoil acts much like a cambered airfoil at angles of attack greater than zero. The increase in pressure drag is partially offset by the decrease in viscous drag due to the negative shear stresses in the valleys, leading to a net increase of total drag. This increase in drag reduces the lift-to-drag ratio significantly. The corrugated profile has also exhibited similar vortex shedding frequencies and lift oscillation amplitudes as the flat plate. This
evidence seems to indicate that the corrugated airfoil is not intended for aerodynamic improvement but instead for structural benefits, as previously hypothesized by other researchers [11,12].

V. Structural Analysis

A. Structural Setup

The structural simulation performed here was similar to Kesel et al.’s [10] finite element analysis of the structural benefit of the Aeshna cyanea forewing. Instead of reconstructing the forewing of the Aeshna cyanea, it was decided to create a 3-D homogeneous profile of the wingspan to test the structural properties of the corrugated profile. The corrugated wingspan was compared with a flat plate wingspan. Each wing was created using the SolidWorks 2009 [21] designer, and then it was tested using the program’s own structural simulation tools.

B. Material Properties and Modeling

To model a dragonfly’s wing, the 3-D wing will be given the properties of chitin. Each model was assumed to have a material with an isotropic nature. The properties of chitin were taken from Kesel [13], which list the Young’s modulus as 6.1 GN/m² and an assumed Poisson’s ratio of 0.25. Each model was then subjected to a pressure load of $4.061 \times 10^{-6}$ GN/mm², which provides a homogenous wing loading that approximates the weight of the dragonfly.

Several models of the corrugation and flat plate were created, varying the percent thickness of each from 1 to 6%. Each wing had a chord length of 1 cm and a span of 4 cm, which are approximations of the dimensions of the Aeshna cyanea forewing; Fig. 12 shows a sample of the models produced.

The maximum displacement of the various profile thicknesses of the flat plate and corrugated profile were measured. Figure 13a graphs the displacement of each thickness. The flat plate shows little resistance to displacement at its thinnest thickness. The 1% flat plate deflects approximately 2.5 mm under load. However, the corrugated profile demonstrates a much higher rigidity in comparison. Its deflection was 35 times lower than the flat plate. Past a 3% thickness, the flat plate shows little improvement on deflection reduction, while the corrugated wing shows little to no change.

A similar trend is seen with the average stress across the wings, as previously seen with the deflection. The flat plate shows much higher average stress at lower thicknesses, but past 3%, the reduction of stress decreases slower as the thickness increases. Figure 13b graphs the average stress on each wing. At 1%, the corrugated wing shows eight times less average stress than the flat plate. The corrugation
again shows its superior ability to handle loading more efficiently than the flat plate without increasing the thickness of the wing. Like the deflection trend, the normalized stress ratio also begins to fall as plate thickness increases.

VI. Conclusions

Numerical simulations were performed to understand the aerodynamic and structural characteristics of a corrugated airfoil. The aerodynamics was studied by solving the incompressible Navier–Stokes equations on an overlapping grid, while the structural characteristics were investigated using commercial software SolidWorks 2009. It was observed that the corrugated airfoil produces similar lift as a flat plate, but at peak gliding ratios, it produces more drag. This increase in drag is due to the higher pressure drag resulting from the thicker virtual streamlined profiles created by the stagnant vortices trapped in the valley. The higher pressure drag is partially offset by the negative shear stresses from the rotating vortices. The lift oscillations of both the flat plate and the corrugated profile were identical with similar vortex shedding frequencies at higher angles of attack. This shows that the corrugations do not interfere with the vortex shedding. However, compared with a flat plate, the flat plate produces more favorable aerodynamic characteristics. Overall, the aerodynamic analysis showed that the selected corrugated profile provides no advantages in terms of stall delay or lift generation. This conclusion is contrary to other studies at much higher Reynolds numbers.

Investigating the structural properties of the corrugated wing and flat plate showed that, under a static loading, the corrugated wingspan had superior performance compared with the flat plate in terms of bending resistance. The study showed that the corrugated wing can reduce deflection and stress on the wing. It would take a flat plate with three times the thickness to perform as well as the corrugated wing. By using corrugation, it has been shown that increased structural rigidity can be obtained with minimum increase in materials.

These two studies provide strong evidence that the corrugated profile is primarily used for structural support in gliding flight at low Reynolds numbers. It provides similar lift, higher drag, and vastly more rigid lift surface.

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References


