An Experimental Investigation on a Bio-inspired Corrugated Airfoil

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An experimental study was conducted to investigate the aerodynamic characteristics of a bio-inspired corrugated airfoil compared with a streamlined airfoil and a flat plate at the chord Reynolds number of Re= 58,000 ~ 125,000 to explore the potential applications of such bio-inspired corrugated airfoils for micro air vehicle (MAV) designs. In addition to measuring the aerodynamic lift and drag forces acting on the tested airfoils, a digital particle image velocimetry system was used to conduct detailed flowfield measurements to quantify the transient behavior of vortex and turbulent flow structures around the airfoils. The measurement result revealed clearly that the corrugated airfoil has better performance over the streamlined airfoil and the flat plate in providing higher lift and preventing large-scale flow separation and airfoil stall at low Reynolds numbers. The detailed flow field measurements were correlated with the aerodynamic force measurement data to elucidate underlying physics to improve our understanding about how and why the corrugation feature found in the dragonfly wings holds aerodynamic advantages for low Reynolds number flight applications.

Nomenclature

AOA   = Angle of attack
C     = Chord length
C_D   = Drag coefficient, \( C_D = D/(\frac{1}{2} \rho V_{\infty}^2 C) \)
C_L   = Lift coefficient, \( C_L = L/(\frac{1}{2} \rho V_{\infty}^2 C) \)
D     = Drag force
L     = Lift force
Re    = Reynolds number
T.K.E = Normalized turbulent kinetic energy \( T.K.E. = (\bar{u}'^2 + \bar{v}'^2)/(2V_{\infty}^2) \)
\( \bar{u}', \bar{v}' \) = turbulent velocity fluctuations
V_{\infty} = Incoming flow velocity
\( \rho \) = Air density
\( \omega_z \) = Spanwise vorticity

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1. Introduction

Micro-Air-Vehicles (MAVs), which typically refer to palm-sized aircraft (e.g. with a maximal dimension on the order of 15 cm and a flight speed of about 10m/s), are of great interest to both military and civilian applications. Equipped with video cameras, transmitters or sensors, these miniaturized aerial vehicles can perform surveillance, reconnaissance, targeting, or bio-chemical sensing tasks at remote, hazardous or dangerous locations. Numerous civil and military applications of MAVs have been proposed, and far more have yet to be imagined. A concerted effort supported by the Defense Advanced Research Projects Agency (DARPA) in recent years has resulted in advancements in miniaturized digital electronics, micro fabrication, miniaturized power cells, remote communication, imaging and control devices and other enabling technologies. Such advances have turned the concept of MAVs as rapidly deployable eyes-in-the-sky from fiction into demonstrated facts. The continuing demand for smaller and robust miniaturized aerial vehicles is making MAV an emerging sector of the aerospace market, and such miniaturized aerial vehicles are expected to become commonplace in the next ten to twenty years.

Although a number of MAVs, either in fixed wing or flapping wing designs, have already been developed by universities, commercial, and government-funded endeavors, the airfoil and wing planform designs for many existing MAVs rely mainly on “scaled-down” reproductions of those used by conventional “macro-scale” aircraft. Chord Reynolds number (Re_c), which is based on airfoil chord length and flight velocity, is usually used to characterize the aerodynamic performance of an airfoil/wing. While traditional, “macro-scale” aircraft have a chord Reynolds number of about $10^6 \sim 10^8$, the low flight speed and miniaturized size of MAVs make their chord Reynolds numbers are typically in the range of $10^3 \sim 10^5$. The aerodynamic design principles applicable to traditional, “macro-scale” aircraft may not be used for MAVs due to the significant difference in chord Reynolds numbers [1-3]. As a result, airfoil shape and wing planform designs that are optimized for traditional, “macro-scale” aircraft are found to degrade significantly when used for MAV designs. Therefore, it is very necessary and important to establish novel airfoil shape and wing planform design paradigms for MAVs in order to achieve improved aerodynamic performance as well as their flight agility and versatility.

A number of insects including locusts, dragonflies, and damselflies employ wings that are not smooth or simple cambered surfaces. The cross-sections of the wings have well-defined corrugated configurations [4, 5]. Such corrugated design was found to be of great importance to the stability of the ultra-light wings to handle the spanwise bending forces and mechanical wear that the wing experiences during flapping. The corrugated wing design does not appear to be very suitable for flight since it would have very poor aerodynamic performance (i.e. low lift and extremely high drag) according to traditional airfoil design principles. However, several studies on corrugated dragonfly wings in steady flow or gliding flight [4-11] have led to a surprising conclusion: a corrugated dragonfly wing could have comparable or even better aerodynamic performances (i.e., higher lift and bigger lift-to-drag ratio) compared with conventional streamlined airfoils in the low Reynolds number regime where dragonflies usually fly.

Most of the earlier experimental studies were conducted mainly based on the measurements of total aerodynamic forces (lift and drag) of either natural dragonfly wings or modeled corrugated wing sections. Detailed studies were conducted more recently to try to elucidate the fundamental physics of the dragonfly flight aerodynamics [12-17]. A number of hypotheses have been suggested to explain the fundamental mechanism of the rather unexpected aerodynamic performance improvement of the corrugated dragonfly airfoils or wings over conventional smooth airfoils. Rees [4] suggested that airflow could be trapped in the valleys of the corrugated structures to become stagnant or rotate slowly in the valleys, resulting in the corrugated wing acting as a streamlined airfoil. Newman et al. [5] suggested that the improved aerodynamic performance would be associated with the earlier reattachment of the flow separation on the corrugated wings. As the angle of attack increases, airflow would separate from the leading edge to form a separation bubble, and the separated flow would reattach sooner due to the corrugation compared with smooth airfoils. Based on pressure measurements on the surfaces of a dragonfly wing model in addition to total lift and drag force measurements, Kesel [12] reported that negative pressure would be produced at the valleys of the corrugated dragonfly wing model, which would contribute to the increased lift. Vargas & Mittal [15] and Luo & Sun [16] conducted numerical studies to investigate the flow behaviors around corrugated dragonfly wings. Their simulation results confirmed the existence of small vortex structures in the valleys of the corrugated dragonfly airfoil. The small vortex structures in the valleys of the corrugated cross section were also revealed qualitatively in the flow visualization experiments of Kwok & Mittal[17].

Despite different explanations about the fundamental mechanism for the improved aerodynamic performance, most of the studies agree that corrugated dragonfly airfoils or wings work well in low Reynolds number regimes, which naturally point to the potential applications of employing such corrugated airfoils or wings in micro-air-...
vehicles. With this in mind, we conducted the present study to try to leverage the corrugation feature of dragonfly wings and to explore the potential applications of such non-traditional, bio-inspired corrugated airfoils to MAV designs for improved aerodynamic performance.

Although several experimental studies have already been conducted previously to investigate the aerodynamic performance of corrugated dragonfly airfoils or wings, majority of previous studies on dragonfly wings or modeled dragonfly airfoils were conducted from a biologist point of view to try to understand the fundamental mechanism of dragonfly flight mechanics, thus, the chord Reynolds number level of those studies is usually relatively small (i.e., \( \text{Re} \leq 10,000 \)). The present study is conducted from the viewpoint of an aerospace engineer to explore the potential applications of such non-traditional, bio-inspired corrugated airfoils in MAV designs. Thus, we chose to conduct the present study at the chord Reynolds number of \( \text{Re} = 58,000 \sim 125,000 \), i.e., in the range where MAVs usually operate, which is much higher than those previous experiments to study dragonfly flight aerodynamics.

In the present study, we report a detailed experimental investigation to quantify the flow behavior around a bio-inspired corrugated airfoil, compared with a streamlined airfoil and a flat plate at in the Reynolds numbers range where MAVs usually operate. The experimental study was conducted in a wind tunnel with Particle Image Velocimetry (PIV) to make detailed flowfield measurements in addition to total aerodynamic force (drag and lift) measurements. The detailed flow field measurements are correlated with aerodynamic force/moment measurements to elucidate underlying fundamental physics to explore/optimize design paradigms for the development of novel, bio-inspired corrugated airfoils for MAV applications.

II. Experimental Setup and Studied Wings

The experimental study was conducted in a closed-circuit low-speed wind tunnel located in the Aerospace Engineering Department of Iowa State University. The tunnel has a test section with a 1.0 × 1.0 ft (30 × 30 cm) cross section and the walls of the test section are optically transparent. The tunnel has a contraction section upstream of the test section with honeycombs, screen structures and a cooling system installed ahead of the contraction section to provide uniform low turbulent incoming flow into the test section.

Figure 1 depicts the three airfoils used in the present study: a bio-inspired corrugated airfoil, a streamlined profiled airfoil and a flat plate airfoil. The cross section of the bio-inspired corrugated airfoil corresponds to a typical cross-section of a dragonfly wing, which was digitally extracted from the profile given in Vargas & Mittal [15]. The profiled airfoil was formed by tautly wrapping a thin film around the bio-inspired corrugated airfoil in order to produce a smooth surfaced airfoil. The flat plate has a rectangular cross section with no rounding at the leading and trailing edges. The flat plate and the bio-inspired corrugated airfoil are made of wood plates with a thickness of 4.0 mm. The maximum effective thickness of the corrugated airfoil (i.e., the airfoil shape formed by fitting a spline through the protruding corners of the corrugated cross section) is about 15% of the chord length, which is as the same as the maximum thickness of the profiled airfoil. The bio-inspired corrugated airfoil and the profiled airfoil...
have the same chord length, i.e., \( C = 101\) mm. The flow velocity at the inlet of the test section was changed from 7.0 m/s to 15.0 m/s for the present study, which corresponds to a chord Reynolds number changing from 58,000 to 125,000. The turbulence intensity of the incoming stream was found to be within 1.0\%, measured by using a hot-wire anemometer.

\[ \text{Figure 2: Experimental setup for PIV measurements} \]

Figure 2 shows the experimental setup used in the present study for PIV measurements. The test airfoils were installed in the middle of the test section. A PIV system was used to make flow velocity field measurements along the chord at the middle span of the airfoils. The flow was seeded with 1–5 \( \mu \)m oil droplets. Illumination was provided by a double-pulsed Nd:YAG laser (NewWave Gemini 200) adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm with a repetition rate of 10 Hz. The laser beam was shaped to a sheet by a set of mirrors, spherical and cylindrical lenses. The thickness of the laser sheet in the measurement region is about 0.5 mm. A high resolution 12-bit (1376 x 1040 pixel) CCD camera (SensiCam-QE, CookeCorp) was used for PIV image acquisition with the axis of the camera perpendicular to the laser sheet. The CCD cameras and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a Digital Delay Generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and image acquisition.

Instantaneous PIV velocity vectors were obtained by a frame to frame cross-correlation technique involving successive frames of patterns of particle images in an interrogation window 32x32 pixels. An effective overlap of 50\% of the interrogation windows was employed in PIV image processing. The PIV measurements were conducted at two spatial resolutions: a coarse level to study the global features of the flow fields around the airfoils with the measurement window size of about 200 mm x 160 mm; and a finer level to investigate the detailed flow structures near the leading edges of the airfoils with the measurement window size of about 50 mm x 40 mm. The effective resolutions of the PIV measurements, i.e., grid sizes, were \( \Delta / C = 0.048 \), and 0.012, respectively. After the instantaneous velocity vectors \((u, v)\) were determined, instantaneous spanwise vorticity \((\omega_z)\) could be derived. The time-averaged quantities such as mean velocity \((U, V)\), ensemble-averaged spanwise vorticity, turbulent velocity fluctuations \((u', v')\) and normalized turbulent kinetic energy (i.e., \( T.K.E. \)) distributions were obtained from a cinema sequence of 280 frames of instantaneous velocity fields. The measurement uncertainty level for the velocity vectors is estimated to be within 2.0\%, and that of the turbulent velocity fluctuations \((u', v')\) and \( T.K.E. \) are about 5.0\%. The aerodynamic forces (lift and drag) acting on the test airfoils were also measured by using a force-moment sensor cell (JR3, model 30E12A-I40). The force-moment sensor cell is composed of foil strain gage bridges, which are capable of measuring the forces on three orthogonal axes, and the moment (torque) about each axis. The precision of the force-moment sensor cell for force measurements is ±0.25\% of the full scale (40N).
III. Experimental Results and Discussions

A. Aerodynamic Force Measurement Results

Figure 3 shows the aerodynamic force measurement results in the terms of lift coefficient and drag coefficient of the studied airfoils as the angles of attack (AOA) of the airfoils changed from 0.0 to 20.0 degrees and Reynolds numbers changed from 58,000 to 125,000.

As shown in Fig. 3, for the flat plate, while the lift coefficient was found to increase almost linearly with the increasing angle of attack, the drag coefficient was found to be reasonable small when the angle of attack is relatively low (AOA<6.0 degrees). As the angle of attack becomes relatively high (i.e., AOA > 6.0 degrees), the increasing rates of the lift coefficient profiles were found to decrease significantly and almost flatten out. The drag coefficients of the flat plate were found to increase rapidly at AOA>6.0 degrees. Such measurement results indicate that stall would occur at AOA=8.0 for the flat plate, which was confirmed from the PIV measurement results to be discussed later. The measurement results also revealed that the lift coefficient of the flat plate would increase slightly with the increasing Reynolds number. The increase rates of the lift coefficient profiles at relatively low angles of attack were also found to increase with the increasing Reynolds number, approaching to the prediction based on inviscid thin airfoil theory (i.e., \( \frac{dC_L}{d\alpha} = 2\pi\alpha \)) at relatively high Reynolds numbers (i.e., Re=125,000). As it is expected, the drag coefficient of the flat plate was also found to increase slightly with the increasing Reynolds numbers.

The lift coefficient of the corrugated airfoil was found to increase almost linearly with the increasing angle of attack, and reach its peak value at AOA ≈12.0 degrees. Then, the lift coefficient of the corrugated airfoil was found to decrease with the increasing angle of attack at AOA>12.0 degrees. The drag coefficient of the corrugated airfoil was found to increase slightly with the increasing angle of attack when the angle of attack is relatively small (i.e., AOA<10.0 degrees). Then, the increasing rates of the drag coefficient profiles were found to become much more significantly at AOA>12.0 degrees. Such measurement results indicate that airfoil stall would take place at AOA=12.0 degrees. For the corrugated airfoil, the increasing rate of the lift coefficients at relatively small angles of attack was found to be much smaller than that of the prediction based on thin airfoil theory (i.e., \( \frac{dC_L}{d\alpha} = 2\pi\alpha \)). The measurement results also revealed that the Reynolds numbers have almost no effects on the aerodynamic performance (i.e., lift and drag coefficients) of the corrugated airfoil.

Although the profiled airfoil was formed simply by tautly wrapping a thin film around the corrugated airfoil, the aerodynamic performance of the profiled airfoil was found to be significantly different from the corrugated airfoil. As shown in Fig. 3(C), when the Reynolds numbers is relatively low (i.e., Re=58,000), the lift coefficient of the profiled airfoil was found to increase linearly at first with the increasing angle of attack at AOA<8.0 degrees, and then flatten out at relatively high angle of attack (i.e., AOA>8.0 degrees), which is quite similar as that of the thin flat plate. As the Reynolds numbers increase, the linearly increasing region of the lift coefficient profiles at relatively small angles of attack was found to become wider and wider. When the Reynolds numbers becoming relatively high (i.e., Re=125,000), the lift coefficient of the profiled airfoil was found to reach its maximum value at AOA ≈ 10.0 degrees, then became to decrease with the increasing angle of attack, which is a typical behavior of a streamlined airfoil at relatively high Reynolds numbers. The measurement results also indicate that the stall angle for the profiled airfoil would increase with the increasing angle of attack, as it is expected.

Fig. 4 shows the comparisons of the measured lift and drag coefficients of the three studied airfoils at two tested Reynolds number levels. It can be seen clearly that, at relatively low Reynolds number (i.e., Re=58,000), the corrugated airfoil was found to have the highest lift coefficient among the three tested airfoils. As is expected, the thin flat plate was found to have the smallest drag coefficient. Both the profiled airfoil and flat plate would stall at AOA ≈8.0 degrees, the airfoil stall was found to be delayed up to AOA≈12.0 degrees for the corrugated airfoil. Such measurement results indicate that the corrugated airfoil could delay the airfoil stall compared with the profiled airfoil and flat plate at relatively low Reynolds numbers.

As described above, while the aerodynamic performance of the corrugated airfoil is almost insensitive to the Reynolds numbers, the aerodynamic performance of the profiled airfoil was found to be improved greatly with the increasing Reynolds numbers. As a result, the profiled airfoil was found to have better aerodynamic performance (i.e., higher lift coefficients and smaller drag coefficients) compared with corrugated airfoil when the Reynolds number becomes relatively high (i.e., Re=125,000). Such aerodynamic force measurement results indicate that the corrugation feature found in dragonflies can bring aerodynamic benefits only for low Reynolds number applications.
Fig. 3: Measured aerodynamic lift and drag coefficients of the studied airfoils
With the findings derived from the aerodynamic force measurements in mind, PIV measurements were carried out to visualize the transient behavior of vortex and turbulent flow structures around the three tested airfoils in order to reveal the underlying fundamental physics associated with the airfoil aerodynamic performance characteristics revealed from the aerodynamic force measurements.

Figure 5 shows the typical instantaneous and ensemble-averaged flow velocity fields around the test airfoils at AOA=6.0 degrees with the Reynolds number Re=58,000. For the flat plate, as revealed clearly from the PIV measurement results given in Fig. 5A, incoming fluid streams were found to separate from the surface of the flat plate right from the leading edge, and then, reattach to the upper surface of the flat plate at the rear portion of the flat plate, i.e., a circulation bubble was found to form on the upper surface near the leading edge of the flat plate. Due to the reattachment of the separated fluid streams, no apparent flow separation or large circulation region was found in the wake of the flat plate.

As shown in the PIV measurement results given in Fig. 5B, incoming flow streams were found to flow smoothly along the upper surfaces of the profiled airfoil. Because the incoming flow streams could flow smoothly to follow the streamlined surfaces of the profiled airfoil at AOA=6.0 degrees, they left the airfoil trailing edge smoothly, which resulted in a relatively small wake region (i.e., the region with velocity deficits) downstream of the airfoil. The small wake region downstream of the airfoil would indicate a small aerodynamic drag force acting on the airfoil, which was confirmed from the aerodynamic force measurements given in Fig. 3.
Figure 5: PIV measurement results with AOA=6.0 (Re=58,000)
Figure 6: PIV measurement results with AOA=12.0 (Re=58,000)
Figure 7: PIV measurement results with AOA=14.0 (Re=58,000)
For the corrugated airfoil, the existence of small circulation bubbles sitting in the valleys of the corrugation cross section of the airfoil can be seen clearly from the measurement results given in Fig. 5C (enlarged views are given later). High-speed flow streams outside the corrugation valleys were found to flow smoothly along a virtual “envelope” profile constructed by fitting a spline through the protruding corners of the corrugated cross section (i.e., a smooth shape formed by tautly wrapping a thin film around the corrugated airfoil). No apparent large-scale flow separation or circulation region could be found in the wake of the corrugated airfoil at AOA = 6.0 degrees.

Figure 6 shows the PIV measurement results when the angle of attack of the airfoils increases to 12.0 degrees. For the flat plate, the circulation bubble on the upper surface near the leading edge was found to burst when the angle of attack increased to 12.0 degrees. The high-speed flow streams separated from the upper surface at the leading edge of the flat plate could no longer reattach to the upper surface of the flat plate. Large-scale flow separation was found to occur on entire upper surface of the flat plate (i.e., airfoil stall) due to more severe adverse pressure gradient at 12.0 degrees angle of attack. The flow separation on the upper surface of the airfoil can also be seen clearly from the ensemble-averaged PIV measurement results in the form of a separation bubble near the trailing edge of the airfoil. Because of the flow separation, the size of the wake region (i.e. the region with velocity deficits) downstream of the flat plate was found to be increased greatly, which indicates an increased aerodynamic drag force acting on the flat plate. The increased aerodynamic drag acting on the flat plate at AOA = 12.0 deg. was confirmed quantitatively for the measured drag-coefficient data given in Fig. 3.

As shown in the results given in Fig. 6B, incoming flows streams were found to flow smoothly along the streamlined nose of the profiled airfoil, as expected. However, large-scale flow separation was found to take place at most portion of the airfoil upper surface at AOA=12.0 degree. Such flow pattern indicates that profiled airfoil was found to stall, resulting in a large circulation region in the wake of the airfoil. The large deficit of the velocity profile in the wake of the profiled airfoil would indicate a rapid increase of the aerodynamic drag force acting on the airfoil due to the airfoil stall, which was confirmed from the drag force measurement data given in Fig. 3. However, for the corrugated airfoil, high-speed fluid streams were still found to follow the “envelope” profile of the corrugated cross section faithfully. No large-scale flow separation could be found over the upper surface of the corrugated airfoil at AOA=12.0 degrees.

The adverse pressure gradient over the upper surface of the airfoils would become more and more severe as the angle of attack increased. Compared with those at 12.0 degrees angle of attack, the circulation regions in the wakes of the profiled airfoil and the flat plate were found to be enlarged significantly when the angle of attack increased to 14.0 degrees (Fig. 7A and Fig. 7B), which would indicate increased aerodynamic drag forces acting on the airfoils. Because of the severe adverse pressure gradient at AOA=14.0 degrees, high-speed flow streams around the corrugated airfoil were not able to follow the “envelope” profile of the corrugated cross section any longer. Large-scale flow separation was found to occur over almost the entire upper surface of the corrugated airfoil (Fig. 7C), i.e., airfoil stall was also found for the corrugated airfoil at AOA=14.0 degrees.

The PIV measurement results demonstrated clearly that the corrugated airfoil could delay large-scale flow separation and airfoil stall to a much higher angle of attack (up to about 12.0 degrees) compared with the profiled airfoil (airfoil stall at AOA=8.0 degrees) and the flat plate (airfoil stall at AOA=6.0 degrees) at low Reynolds numbers. In order to elucidate the fundamental mechanism why corrugated airfoils have better performance in preventing large-scale flow separation and delaying airfoil stall compared with the profiled airfoil and flat plates at low Reynolds numbers, refined PIV measurements near the leading edges of the airfoils were made to investigate detailed flow structures around the leading edges of the airfoils. The refined PIV measurement results are given in Fig. 8 and Fig. 9.

As described in the review articles of Lissaman [19], Gad-el-Hak [20] and Carmichael [21], for streamlined airfoils at low Reynolds numbers, the boundary layers would remain laminar at the onset of the pressure recovery unless artificially tripped. Laminar boundary layers are unable to withstand any significant adverse pressure gradient. Therefore, the aerodynamic performances of streamlined airfoils at low Reynolds numbers are entirely dictated by the relatively poor separation resistance of the laminar boundary layers. The laminar boundary layer over the profiled airfoil was visualized clearly as a thin vortex layer over the nose of the airfoil in the instantaneous vorticity distribution given in Fig. 8. As indicated in the PIV measurement results, the laminar boundary layer would separate from the upper surface of the profiled airfoil at AOA=12 degrees since the laminar boundary layer has very poor capacity to overcome the adverse pressure gradient. The separated laminar boundary layer would behave more like a free shear layer, which is highly unstable; therefore, rolling-up of Kelvin-Helmholtz vortex structures and transition to turbulence would be readily realized. Because of the laminar nature of the flow around the nose of the
streamlined airfoil, the regions with higher turbulent kinetic energy (T.K.E.) were found to be confined within the thin separated shear layer.

Flow around the leading edge of the corrugated airfoil is much more involved than those the profiled airfoil. As visualized in the PIV measurement results given in Fig. 8, due to the sharp leading edge, incoming fluid streams were found to separate from the corrugated airfoil right from the sharp leading edge to form a laminar shear layer at first. Then, the separated laminar boundary layer was found to be transition to turbulent rapidly as it approached the first protruding corner of the corrugated airfoil. Unsteady vortices were found to shed periodically from the protruding corners of the corrugated cross section, i.e., the protruding corners of the corrugated airfoil seem to act as “turbulators” to generate unsteady vortex structures that promote the transition of the separated boundary layer from laminar to turbulent. For the profiled airfoil at the same angle of attack of AOA=12 degrees, the turbulent transition and the generation of the unsteady vortex structures were found to take place in the regions relatively far away from the surfaces of the airfoils. For the corrugated airfoil, the turbulent transition and the generation of the unsteady vortex structures were found to take place in the region quite close to the protruding corners of the corrugated airfoil. The unsteady vortex structures were found to be trapped in the valleys of the corrugated cross section, which would interact with the high-speed flow streams outside the valleys dynamically. Due to the interaction between the unsteady vortex structures and outside high-speed fluid streams, high-speed fluid was found to be pumped from outside to near wall regions (the pumping effect of the unsteady vortex structures to move high-speed fluid from outside to near wall regions can be seen clearly from the animations of the time sequence of instantaneous PIV measurements). The pumping of high-speed fluid to near wall regions provided sufficient kinetic energy for the boundary layer to overcome the adverse pressure gradient to suppress large-scale flow separation and airfoil stall. The mean velocity vectors and corresponding streamlines revealed clearly that small circulation bubbles would be formed in the valleys of the corrugated airfoil. High-speed fluid streams outside the valleys would flow smoothly along the “envelope” profile of the corrugated cross section (i.e., the dashed profile). The rotation direction of the circulation bubbles in the valleys was found to be clockwise (flow moving from left to right) to accommodate the high-speed fluid streams outside the valleys. For the corrugated airfoil, the rapid transition of the boundary layer from laminar to turbulent due to the effect of the protruding corners as “turbulators” could also be seen clearly from the measured T.K.E. distribution, which resulted in a much higher T.K.E. level in the near wall regions.

It should be noted that Vargas & Mittal [15] conducted a numerical study to investigate flow structures around a similar corrugated airfoil as the one used in the present study, but at a much lower Reynolds number level of Re=10,000. Despite the difference in Reynolds number of the two studies, the measurement results of the present study were found to agree well with the numerical simulation of Vargas & Mittal [15] in revealing the global pattern of the flow field around the corrugated airfoil and the small vortex structures in the valleys of the corrugated cross section.

Compared with those of the profiled airfoil, the “energetic” turbulent boundary layer over the upper surface of the corrugated airfoil would be much more capable of advancing against adverse pressure gradient suppressing flow separation [19, 20]. Therefore, flow streams would be able to attach to the “envelope” profile of the corrugated airfoil faithfully even at much larger angle of attack (up to AOA=12.0 degrees), while the large-scale flow separation and airfoil stall had already been found to take place for the profiled airfoil.

As shown in Fig. 9, although the separated laminar boundary layer was found still to be transition to turbulence rapidly by generating unsteady Kelvin-Helmholtz vortex structures in the flow field when the angle of attack increases to 14.0 degrees, the shedding path of the unsteady vortex structures was found to be relatively far from the surface of the corrugated airfoil. The unsteady vortex structures could no longer be trapped in the valleys of the corrugation. The ensemble-averaged velocity field and the corresponding streamlines also show clearly that the high-speed flow streams permanently separate from the upper surface of the airfoil. Although small circulation bubbles were still found to sit in the valleys of the corrugated cross section, they became much weaker (i.e., much lower rotating velocity as revealed from the velocity distributions), and their rotating direction was also found to be reversed to accommodate the reversed flow outside the valleys. The adverse pressure gradient over the upper surfaces of the airfoils would become much more significant as the angle of attack increased to 14.0 degrees, which requires a much more energetic boundary layer to overcome the adverse pressure gradient over the upper surface of the airfoil. However, the measured T.K.E. distribution reveals that the regions with higher turbulent kinetic energy were along the shedding path of the Kelvin-Helmholtz vortex structures, which is quite far from the surface of the corrugated airfoil. Therefore, large-scale flow separation and airfoil stall were found to take place on the corrugated airfoil due to the lack of enough kinetic energy in the boundary layer to overcome the significant adverse pressure gradient.

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a. Instantaneous velocity fields

b. Streamlines of the instantaneous flow fields

c. Ensemble-averaged velocity fields

d. Streamlines of the ensemble-averaged flow fields

e. Normalized turbulent kinetic energy distributions

A. profiled airfoil

B. Corrugated airfoil

Figure 8: Refined PIV measurements with AOA=12.0 (Re=58,000)
Figure 9: Refined PIV measurements with AOA=14.0 (Re=58,000)
Concluding Remarks

An experimental study was conducted to investigate the aerodynamic characteristics and flow features around a bio-inspired corrugated airfoil compared with a streamlined airfoil and a flat plate at chord Reynolds number of $Re=58,000 \sim 125,000$ to explore the potential applications of non-traditional, bio-inspired corrugated airfoils for MAV applications. The experimental study was conducted in a wind tunnel with Particle Image Velocimetry (PIV) to make detailed flow field measurements in addition to total aerodynamic force measurements. The detailed flow field measurements were correlated with the aerodynamic force measurement data to elucidate underlying physics to improve our understanding about how and why the corrugation feature found in the dragonfly wings holds aerodynamic advantages for low Reynolds number flight applications. The key to designing better airfoils for improved aerodynamic performance of MAVs is to know how to exploit the advantages of the corrugation feature and knowing its limitations.

The aerodynamic force measurements revealed that, compared with the streamlined airfoil and flat plate, the corrugated airfoil could generate higher lift and delay airfoil to much higher angle of attack for low Reynolds number flight applications ($Re<100,000$). While aerodynamic performance of the streamlined airfoil and the flat plate would vary considerably with the changing of the Reynolds numbers, the aerodynamic performance of the corrugated airfoil was found to be almost insensitive to the Reynolds numbers.

The detailed PIV measurements elucidated underlying physics about how and why corrugated airfoils could suppress large-scale flow separation and airfoil stall at low Reynolds numbers. It was found that the protruding corrugation corners would act as boundary layer trips to promote the transition of the boundary layer from laminar to turbulent while remaining ‘attached’ to the envelope profile of the high speed streamlines. The valleys of the corrugated cross section of the airfoil would trap unsteady vortex structures that help the boundary layer stay ‘attached’ by pulling high-speed flow into near wall regions. It is by these two processes that the corrugated airfoil can overcome the adverse pressure gradient, thus, discourage large-scale flow separation and airfoil stall.

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