Motion Kinematics Effects on Aerodynamic Performance of Bio-Inspired Wing Sections in Ultra-Low Reynolds Number Flow

Charles Webb\textsuperscript{1}, Haibo Dong\textsuperscript{2}
\textit{Department of Mechanical & Materials Engineering,}
\textit{Wright State University}
\textit{Dayton, OH 45435}

Rajat Mittal\textsuperscript{3}
\textit{Department of Mechanical & Aerospace Engineering,}
\textit{The George Washington University}
\textit{Washington, DC 20052}

“Bio-inspired” wing sections, so aptly named because their profile is defined by corrugated sections observed from actual insect species, have attracted more and more attentions in aircraft wing design. Existing literature has shown that corrugated airfoils, as well as their profiled counterparts, while possessing an unconventional shape, show very little contribution in drag when compared to more technical airfoils such as a flat plate and a cambered conventional airfoil with respect to cruising flight of fixed-wing aircraft. In addition, the corrugated airfoils were shown to delay stall as well provide an increase in translator lift. With this in mind, this study presents a series of computations using two bio-inspired airfoils and two technical airfoils in a flapping motion for various reduced frequencies and Strouhal numbers. We find that for certain values of reduced frequencies and Strouhal numbers that the wake shows no appreciable difference between the four different airfoils. With increasing reduced frequencies and Strouhal numbers we find that the wake begins to vary widely from each other.

\textbf{Nomenclature}

\begin{align*}
y(t) &= \text{Plunge (heave) as function of time} \\
\theta(t) &= \text{Pitch as function of time} \\
A_y &= \text{Amplitude of plunge} \\
h_0 &= \text{Reduced plunge amplitude, } h_0 = A_y/c \\
c &= \text{Airfoil chord} \\
f &= \text{Pitch or plunge physical frequency, Hz} \\
T &= \text{Plunge motion period (seconds)} \\
t/T &= \text{fraction of plunge motion period} \\
k &= \text{Reduced pitch or plunge frequency, } k = \pi f c/u_\infty \\
\theta_o &= \text{Amplitude of pitching motion, deg} \\
x/c &= \text{Airfoil chord fraction, or chord fraction of pivot point location for pitch (trailing edge = 1.0).} \\
St &= \text{Strouhal Number, } St = 2f l/u_\infty = 2kh/\pi \\
\varphi &= \text{Phase of motion, deg; 360\degree = one period of plunge} \\
C_T &= \text{Thrust (or drag) coefficient} \\
C_l &= \text{Lift coefficient} \\
k h &= \text{Nondimensional plunge velocity} = 2\pi f A_y/u_\infty
\end{align*}

\textsuperscript{1} Graduate Student, AIAA Student Member.
\textsuperscript{2} Assistant Professor, AIAA Senior Member.
\textsuperscript{3} Associate Professor, AIAA Associate Fellow.

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I. Introduction

Micro Air Vehicles (MAVs) are aircraft of generally very small physical size. With small chord lengths as well as slow flow speeds, operating Reynolds number range for such vehicles is termed ultra-low Reynolds number range, a phrase coined from Knuz and Kroo (2001). This range is typically from 10 to $10^4$ where viscous effects begin to dominate flow interactions and should not be ignored. Within this flow regime, conventional aerodynamic theory and existing engineering applications breakdown, and just as man looked to nature for inspiration to take to the skies in the first place, researchers with constantly improving equipment and experimental procedures are again turning to nature. Insects specifically have mastered the art of flight in this flow regime (Ellington 1999) with many insect species being “high performance fliers” with hovering capabilities as well as sideways and backwards flight, and therefore, there is a great deal of literature involving idealized airfoil kinematics inspired by motions seen in insects. These studies have primarily been conducted using conventional airfoils like those used on larger fixed wing aircraft, however, with the common goal of a MAV that can match the flight characteristics of insects, it is advantageous to look more into how the insects wings are constructed and not just how they are moved.

Several researchers in the field of biology and other related fields have spent a great deal of effort analyzing the structure of insect wings. Unlike birds which control the shape of their wings by muscle contractions to alter the alignment of the bones and the arrangement of feathers (Kent 1992), insects have less active control as insect wings muscles are restricted to the base of the wing. Therefore, insect wings are passive structures that rely on the vein arrangement, pleated configuration, and material properties to determine how the wing will change shape when aerodynamic forces act upon it (Wootton 1981; 1992). The arrangement in veins, vein diameter, and vein branching varies widely among insect orders and families (Wootton 1990; Combes and Daniel 2003a). As a sequence, a number of insects including locusts, dragonflies, crane flies, and hoverflies employ wings that are pleated along the chord. The pleated configuration of these corrugated wings varies along the spanwise and chordwise direction of the wings allowing for torsion and development of camber while providing stiffening against spanwise bending and an overall since of structural rigidity (Hertel 1966, Newman et al 1977, Newman and Wootton 1986, Sudo and Tsuyuki 2000, Rees 1975a).

The corrugated and profiled airfoils shown in figure 1 look nothing like the airfoils used in common engineering applications, so intuitively it would seem that these kinds of foils would have a poor aerodynamic performance. However, a handful of studies have been performed in which pleated models of the dragonfly wing (Rees 1975b, Rudolph 1977, Newman et al 1977, Bucholz 1986, and Kesel 2000), as well as actual dragonfly wings (Okamato et al 1996) and full body dragonflies (Wakeling and Ellington 2000).
1997a) were placed in a steady flow to replicate gliding flight indicative of the species. It was shown that these airfoils possessed such advantages like delaying stall and providing more lift with a negligible increase in drag when compared to foils such as flat plate at the same angle of attack. The results from these studies, however, vary when trying to answer what effect the pleats have on the aerodynamic performance.

Most recently, wind tunnel experiments as well as computations (Kesel 2000, Tamai et al 2007, Vargas et al 2008) compared the pleated airfoils to their profiled counterparts as well as technical airfoils like the GAW1 and flat plate. The general consensus among these studies is that stagnant or slowly rotating vortices form in the pleats which create a negative shear drag along the chord length effectively creating what can be considered the profiled counterpart. It was also shown in Kesel, and Vargas et al, that the pleated airfoils were at the very least equivalent to the performance of their profiled counterparts if not better in some cases.

In the current study, we describe a sequence of numerical simulations that explore the wake structures and the aerodynamic performance of bio-inspired airfoils vs. conventional technical airfoils undergoing a combined pitch-and-plunge motion. Results are used for understanding of Reynolds number effects and motion kinematics effects including Strouhal number, $St$, reduced frequency, $k$, and the product of reduced frequency and normalized plunge amplitude, $kh$ effects on airfoil performance.

II. Methodology

A. Motion Setup and Airfoils

The motion of an airfoil undergoing combined pitch-and-plunge can be prescribed as the following two equations:

\[
\theta(t) = A_\theta \cos(2\pi f_\theta t + \varphi_\theta)
\]

\[
y(t) = A_y \sin(2\pi f_y t + \varphi_y)
\]

where $A_\theta$ and $A_y$ are the amplitudes of the pitch and plunge of the airfoil, respectively, $f$ is the respective frequencies of motion. The relevant non-dimensional parameters in this study is the normalized plunge amplitude, $h_0 = A_y/c$ the Reynolds number $Re_\infty = u_\infty c / \nu$ (where $u_\infty$ is the freestream velocity, $c$ is the foil chord and $\nu$ is the kinematics viscosity of the fluid) and the Strouhal number $St = 2A_y f / u_\infty$ based on the wake width (Triantafyllou et al 1992, Dong et al 2006). We consider principally cases where the pitch and plunge amplitudes $A_\theta$ and $A_y$ are fixed to amplitudes of 15° and .1, respectively, and physical frequencies of 0.625 Hz and 1.25 Hz, creating reduced frequencies, $k$ of 3.93 and 7.85, and Strouhal numbers, $St$ of 0.25 and 0.5, respectively. The Strouhal number is ultimately dependent on the frequency, free-stream velocity and amplitude of the plunge. The reduced frequency is dependent on these same parameters save for the amplitude of the plunge. Therefore, by solely varying the amplitude of the plunge, it is possible to create cases where the reduced frequency is the same, but the Strouhal number and in turn the reduced plunge frequency, will match that of another case. All cases were run at a Reynolds number of 1,200. Additionally, Reynolds number sweeps of 300, 600 were added to see what if any effect the Reynolds number has on the flows. All studies by varying reduced plunge frequency, the product of reduced frequency and normalized plunge amplitude or $kh$, the Strouhal number, or the shape of the airfoils, are listed in Table 1.
As listed in Table 1, this study involves the two bio-inspired airfoils mentioned above taken from a dragonfly forewing ( ) and a hoverfly wing( ). These two bio-inspired airfoils are compared to two additional “technical” airfoils of a GAW-1 (Hu et al. 2008) and an ellipse of 9% thickness (Dong et al. 2006) as shown in Figure 2. All airfoils have been scaled to a chord length of unity, and maximum thickness of all four airfoils has been normalized to 9% in order to get rid of airfoil thickness effect.

<table>
<thead>
<tr>
<th>Technical airfoils</th>
<th>Bio-Inspired airfoils</th>
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<tr>
<td>(i) Ellipse</td>
<td>(ii) GAW-1</td>
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<td>(iii) Dragonfly forewing</td>
<td>(iv) Hoverfly wing</td>
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Figure 2 Four different airfoils used in current study

<table>
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<th>$h$</th>
<th>$kh$</th>
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<td></td>
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<td>7.85</td>
<td>0.1</td>
<td>0.785</td>
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### B. Computational Method

A second-order finite-difference-based immersed-boundary solver (Mittal et al 2008) is used in this study. Its key feature is that simulations with complex boundaries can be carried out on stationary non-body conformal Cartesian grids, eliminating the need for complicated re-meshing algorithms that are usually employed with conventional Lagrangian body-conformal methods. The method employs a second-order central difference scheme in space and a second-order accurate fractional-step method for time advancement. Detailed validation of the code can be found in (Dong et al 2006, Mittal et al 2008, Ol et al 2008). Based on comprehensive grid and domain size independence studies conducted for the motions studied in the present work, a domain size of $30 \times 30$ and a $515 \times 283$ grid has been chosen for all simulations. A uniform free-stream is specified in the computation, and the airfoil begins moving at time $t=0$, or phase $\phi=0^\circ$.

### III. Results

**a. Fixed reduced plunge amplitude, $h = 0.1c$, and increasing reduced frequency, $k$**

In effort to try to avoid confusion, we present cases in different sets. Concerning the main sets of simulations, all aspects about the airfoil motion were kept constant, especially the reduced
plunge amplitude, and only the frequency of oscillation in both the pitch and plunge were increased to create cases at different reduced frequencies. This is done because later we will present a case where the reduced frequency, \( k \), is equal to 7.85, however the reduced plunge amplitude, \( h \), is halved effectively creating a case where the reduced plunge velocity, \( kh \), is equal to 0.393.

We first turn our attention to the flow field concerning the reduced frequency, \( k = 3.93 \), with the reduced plunge amplitude = 0.1c, effectively creating case where the reduced plunge velocity, \( kh \), is equal to 0.393, not to be confused with the case mentioned in the previous paragraph. Spanwise vorticity contours are shown in the figure below, figure 1, for all four airfoils at the end of the final period of motion based on the plunge frequency. In this figure, as well as all vorticity contours shown in this paper, vorticity contours are shown with 13 different levels between the values of ±36 with the two near zero levels blanked out for clarity. These cases were computed for six periods of motion, a close examination of these plots show that the wake relaxes to what can be called a steady, or time periodic state by \( t/T \) of 3.0 in the form of a familiar inverse Karman vortex street with no other appreciable difference between contour levels for \( t/T = 4.0, 5.0, \) and 6.0. We do notice some small vortices forming on the pressure side of the hoverfly airfoil that seems to be absent in the other airfoils however, the obvious conclusion in this figure is that the flow field for all four respective airfoils is nearly identical at the last phase of motion, as well as all other phases of motion. This assertion is confirmed using the averaged horizontal component of velocity as an additional means of analyzing the behavior of the flow field. The bottom row of figure 2 contains the averaged velocities for all four airfoils at this \( kh = 0.393 \), these results are averaged over the entire six periods of motion and contour levels are clearly shown in the figure this time. Again we see from these plots that the relative shape, strength, and angle of deflection of the wake is nearly identical for all four airfoils. This seems to be consistent with the notion that at high reduced frequencies and values of \( St \) that the shape of the airfoil has no effect on the flow field (At the time of writing this paper, the researcher was unable to explicitly find this conclusion in the literature). The fact that the flow field from each respective airfoil is the same is completely lost on the force coefficients as we see can clear differences between average values as shown in figure 3. We do notice however, that the average lift between the ellipse and the dragonfly airfoils is comparable, \( C_L = -0.197 \) and -0.201, respectively. Also, the GAW-1 and the hoverfly airfoils seem to be the only lift producing airfoils for this particular reduced plunge amplitude, with the hoverfly showing the most promise. Much as we would expect from the flow field, this is a thrust producing cases with all four airfoils showing a positive thrust with all values with in roughly 18% of the mean value.
The cases at a $k = 7.85$ and $h = 0.1c$ (for a $kh = 0.785$) are a different story, computed vorticity contours are shown in figure 4, for all four airfoils at different values of $t/T$. The first and second phase of motion, shows agreeable comparison between vorticity contours for the four respective airfoils just as in the $kh = 0.393$, however, vortex formations start to differ at the third phase. By the end of the 6th period of motion, we see that none of the cases have relaxed to what American Institute of Aeronautics and Astronautics
we could call a steady state solution but more importantly, no comparison can be made between any of the computed contours. These cases were resubmitted for an additional six periods for a total of 12 periods of computed motion. This information suggests that the $kh = 0.785$ cases reach a steady state solution as early as $t/T$ of 7.0, with very little difference in the vorticity for each airfoil for the phases following $t/T = 7.0$. However, each respective airfoil seems to have reached a steady state solution drastically different from the other airfoils and very few arguments can be made for any kind of similarity between the four flow fields.

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<th>(i)</th>
<th>(ii)</th>
<th>(iii)</th>
<th>(iv)</th>
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<tbody>
<tr>
<td>Ellipse</td>
<td>GAW-1</td>
<td>Dragonfly</td>
<td>Hoverfly</td>
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<tr>
<td><img src="image" alt="Ellipse at t/T = 1.0" /></td>
<td><img src="image" alt="GAW-1 at t/T = 1.0" /></td>
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<td><img src="image" alt="Dragonfly at t/T = 6.0" /></td>
<td><img src="image" alt="Hoverfly at t/T = 6.0" /></td>
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Upon a closer look at the vorticity at a $t/T = 12.0$, we observe that the two bio-inspired airfoils, dragonfly forewing and hoverfly wing, have developed a distinct vortex pairing rather than an inverse Karman vortex street like the one seen in the $kh = 0.393$ cases. Also, the hoverfly airfoil’s leading edge activity on the pressure is much less pronounced than in the $kh = 0.393$, with the dragonfly airfoil now showing stronger pressure side activity than the other airfoils. Additionally we observe that the angle of the deflection is completely opposite from each other with the wake produced by the dragonfly airfoil pointing upwards whereas the wake from the hoverfly airfoil pointing downwards. Concerning the dragonfly airfoil, we see complete vortex pair closest to the trailing edge, however, the hoverfly airfoil only shows a negative vortex that curls up nearly underneath trailing edge of the pressure side. The technical airfoils, ellipse and GAW-1, seem to have retained the inverse Karman street vortex, more notably in the case of the GAW-1 airfoil. The ellipse seems to be part way in between a Karman street and vortex pairing with the spacing between the vortices being a little large to be considered a distinct vortex pair. Additionally, as seen with the bio-inspired airfoils, that the angles of deflection are opposite from each other. We once again use averaged velocity components as a secondary means of qualitatively analyzing the flow field. Computed contours for the average x component velocity are shown in above in figure 4(b). If only observing the very near wake, comparisons can be made between the dragonfly and ellipse contours, and between the hoverfly and GAW-1 contours, as each respective pair seem to have relatively the same strength, thickness, and angle.
of jet produced, as well as each pair has the same relative position and strength of negative regions near the trailing edge of the airfoil.

Returning the averaged force coefficients, just as with the flow field, no comparison is possible for average force coefficient results. We note that as with the increased reduced frequency that the magnitudes of the forces are much higher. All cases are thrust producing just as with the \( kh = 0.393 \) cases, however, the ellipse is finally able to produce an average lift whereas the lower frequency case didn’t show an average lift, and the GAW-1 now produces a negative lift whereas it did produce lift at the lower frequency. The dragonfly airfoil still fails to produce lift, however does show good thrust production compared to the other airfoils second only to the hoverfly airfoil which seems to outperform all the other airfoils in both thrust and lift production.

![Graph showing force coefficients for k = 7.85](image)

At this point, we have presented two sets of cases for a total of eight cases, four cases at a reduced frequency of 3.93 and reduced plunge amplitude of 0.1c, and four cases at a reduced frequency of 7.85 and a reduced plunge amplitude of 0.1c. In both sets of cases, all parameters pertaining to the flow and the airfoil motion have been held constant, in the \( k = 3.93 \) cases we have shown that the flow field between all four airfoils were nearly identical; however, as we have increased the frequency to 7.85, we see that a very different flow field results for each respective airfoil. Again, with all things held constant with the exception of the airfoil shape for these four cases, it would seem at this point that the airfoil shape does have an effect on the flow field which possibly even leads to larger differences in the force coefficients. In an effort to begin to bridge the distance between reduced frequencies of the 3.93 and 7.85, we have used the ellipse and dragonfly airfoils in additional simulations at reduced frequencies of 5.02, 6.28, 6.78, 7.23. Below are computed vorticity contours for all four sets of cases for both airfoils at end of the 6th period of motion in figures 8. Starting with the \( k = 5.02 \) set, the flow seems to relax at the
end of the 5\textsuperscript{th} period, with the 5\textsuperscript{th} period and 6\textsuperscript{th} period vorticity contour looking nearly identical. We also see that the flow field between each airfoil is still identical. The same trend is observed in the $k = 6.28$ set though we cannot see a clear relaxed flow field as the four sets afore mentioned cases were only computed for six periods of motion. More important in this case is that we see, save for very small minor differences, that the flow field is largely similar between the two airfoils. Increasing to a $k$ of 6.78 a difference in flow fields is seen at the end of the 5\textsuperscript{th} period (phase not shown), and finally this phenomena seems to happen slightly earlier phase, again not shown, in the set of cases at a $k$ of 7.23, though the point at which the flow field differs and by how much is purely a matter of judgment.

<table>
<thead>
<tr>
<th>$k$</th>
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<td>7.23</td>
<td><img src="image" alt="Ellipse" /></td>
<td><img src="image" alt="Dragonfly" /></td>
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Figure 7

b. Reduced frequency, $k = 7.85$, reduced plunge amplitude, $h = 0.05c$

In an additional effort to try to ascertain what parameters have a more meaningful definition or impact on the flow, all four airfoils were used in a simulation where the plunge amplitude was...
halved to 0.05c. With all other kinematic parameters held constant, this creates a case where the reduced frequency is still large, $k = 7.85$, but the $St$ number and in effect the reduced plunge velocity, $kh$, is equal to that of a $kh = 0.393$ which matches the reduced plunge velocity of the case first presented in this section (Figure 3). Computed vorticity contours are shown in figure 7 for the final phase of motion. In this case, the solution was computed for 10 periods of plunge motion to allow for a steady state solution, which does eventually develop over the $7^{th}$ and $8^{th}$ periods, it seems as though the relaxation to steady state takes just as long as the $k = 7.85$ case (figure 4). The important conclusion from these plots is that, though the wake looks nothing like that seen in the $k = 3.93, h = 0.1c, (kh = 0.393)$ cases shown in figure 3, we see that the four respective flow fields, save for some small differences, are now similar for this final phase, though we note that the comparison is not as strong as it is for the $k = 3.93, h = 0.1c$ cases in figure 3, and while the dragonfly seems to have maintained the kind of wake structure seen in the $kh = 0.785$ case, figure 4(a), we can see the remaining airfoils have completely changed the angle of deflection and structure of the wake when compared to the $kh = 0.785$ case.

<table>
<thead>
<tr>
<th>Ellipse</th>
<th>GAW-1</th>
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<th>Hoverfly</th>
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(a.) Wake structures

| ![Time-Averaged Velocity Contours](image5.png) | ![Time-Averaged Velocity Contours](image6.png) | ![Time-Averaged Velocity Contours](image7.png) | ![Time-Averaged Velocity Contours](image8.png) |

(b.) time-averaged velocity contours

Figure 8 $kh = 0.393, k = 7.85, h = 0.05$

Returning to the subject of averaged force coefficients, we can see that this flow field seen before in the $k = 7.85 h = 0.1c (kh = 0.785)$ cases in figure 5 for the dragonfly forewing, that roughly the same amount of negative lift is produced. Also, since all four airfoils share this flow field, we can see that the other lift coefficients are roughly equal, though the hoverfly seems to be the outlier in this case. Thrust is also remarkably comparable in this case as all four averaged coefficients are within 15% of the mean value. Also, we can note that even though the values for thrust are an order of magnitude higher than the coefficients seen in the $k = 3.93 h = 0.1c$, in

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IV. Summary

We have presented in this study different sets of cases where every parameter concerning the flow and the motion of the airfoil are held constant and only the shape of the airfoil has changed, as we have seen, contrary to conventional wisdom that very different flow fields result from different airfoils as the reduced plunge velocity increases. We see that the similarities among flow fields for each respective airfoils begins to break down somewhere near a reduced plunge velocity of 0.65. Cases where the reduced frequency is high, but reduced plunge amplitude is sufficiently low enough to bring the values of reduced plunge velocity back down to a value of 0.393 has shown similar flow fields between different airfoils however, the lack of comparison between the resulting flow fields from this case ($k = 7.85, h = 0.05c, kh = 0.393$) and the first case presented in the results section ($k = 3.93, h = 0.1c, kh = 0.393$) shows that this parameter of reduced plunge velocity is not sufficient information to predict what the flow field will look like. This study in no way conclusively proves that the shape of the airfoil matters, one possible theory is that as the reduced plunge amplitude increases to a sufficiently high value that more than one steady state solution may result, but again any notion that the shape of the airfoil is a dominant parameter is purely conjecture at this point. We have also seen that even when the flow field for the respective airfoils is similar, different force coefficients may result as seen in the cases represented in figure 3 and 4. In this example, we see that the hoverfly seems to be a superior performer when compared to the other airfoils. It would seem at this point that the shape of the airfoil has a more dominant effect on the lift production than it does for the thrust were for all cases presented, positive thrust was generated. The hoverfly airfoil showed consistently higher lift production along with favorable thrust production. The dragonfly airfoil
on the other hand did not seem to perform as well as it does in static testing as reported by Kessel and other researchers, while producing thrust failed to generate an average lift for any of the cases discussed above. This brings into question as to what role does this wing play since we have only tested the forewing on a quad-winged creature. It would seem through these preliminary findings that bio-inspired wings in this ultra-low Reynolds number range might in fact have a slight advantage over technical airfoils, at least considering the four airfoils tested. And whether the different flow fields observed is in fact a result of the airfoil or some other combination of parameters, it is possible to assume that this field of unsteady aerodynamics might have become more complicated.

IV. Acknowledgement

This is work is supported under Ohio Space Grant Consortium seed grant, Wright State University Research Challenge grant and AFRL/DASGI Ohio Student-Faculty Fellowship program.

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