Lecture # 12: Bio-inspired aerodynamics and Applications for Micro-Air-Vehicle (MAV) applications

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Innovative Bio-inspired Aerodynamic Designs for Unmanned-Aerial-Vehicle (UAV) Applications

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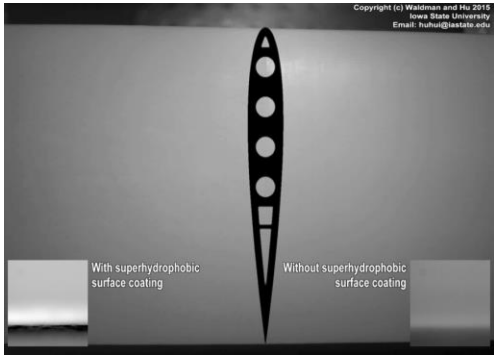
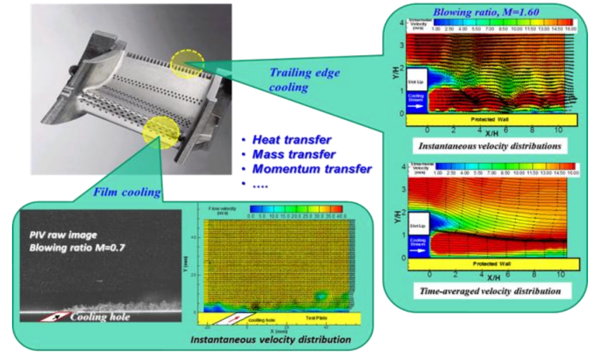
My Research Portfolio

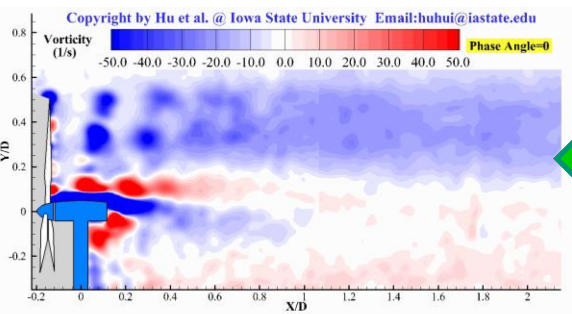


Aircraft icing physics and de-/anti-icing (Sponsors: NASA, FAA, and NSF)

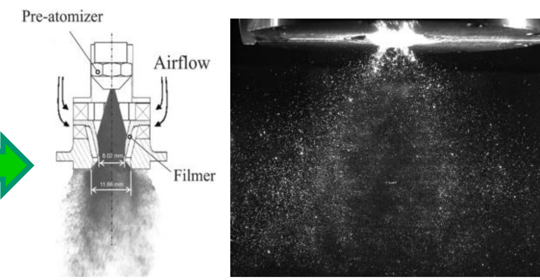


Film Cooling & Heat Transfer of Gas Turbines (Sponsors: AFOSR, DoE, GE)

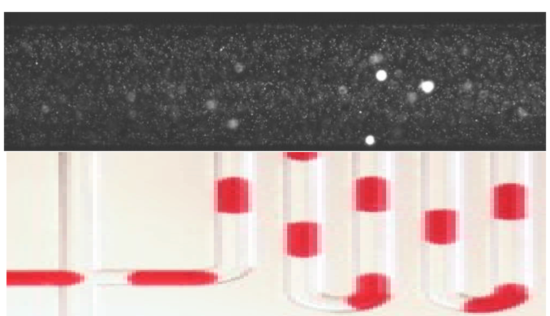
Advanced Flow Diagnostic Technique Development & Instrumentation (PIV, PLIF, MTV, MTT, DIP…)



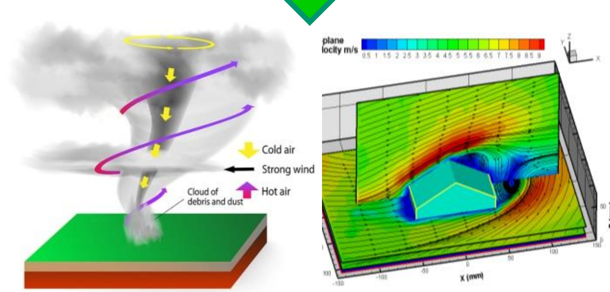
Wind Turbine Aeromechanics (Sponsors: NSF, IEC, DuPont, DoE)



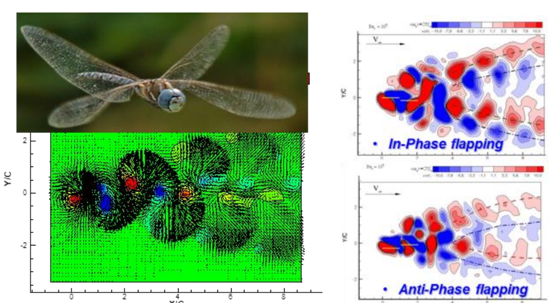
Fuel spray characterization & atomization (Sponsors: NSF, DoE, UTAS, Honeywell)



Microfluidics & Nanofluidics, Micro-scale heat transfer (Sponsors: NSF, AFOSR)



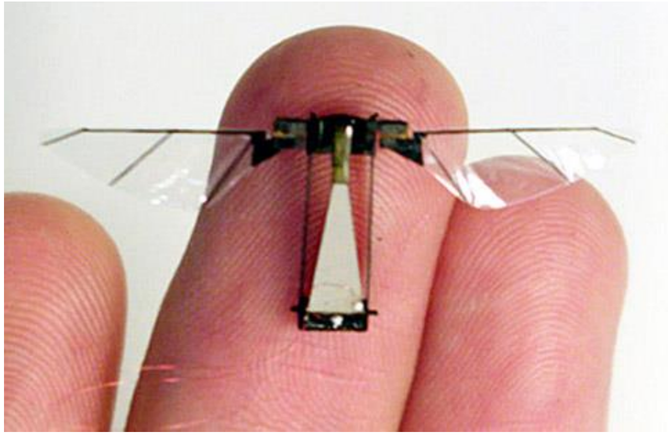
Flow –Structure-Interaction (FSI) of built structures in Tornado, Microburst and Snow/Storms(Sponsors: NSF, NOAA)



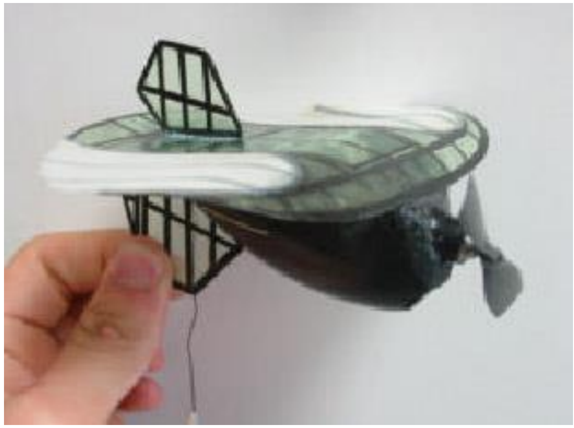
Bio-inspired aerodynamics and bio-inspired UAS designs (Sponsors: AFOSR, NSF)

❑ UAV: Micro Air Vehicles (MAVs) and Nano Air Vehicle (NAV)

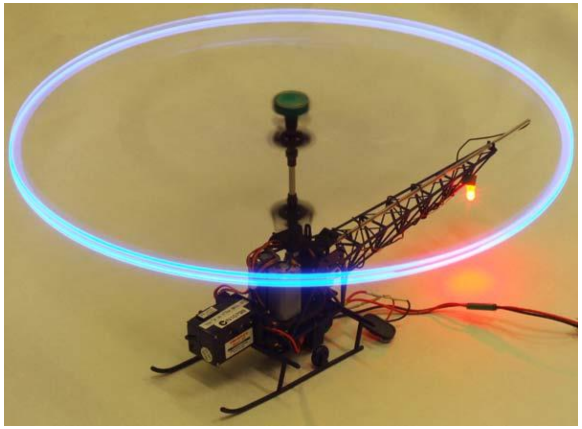
- ***MAVs:*** *small air vehicles with wingspan less than 15 cm and capable of operating at speeds of about 10 m/s.*
- ***NAVs:*** *airborne vehicles no larger than 7.5 cm in length, width or height, capable of performing a useful military mission at an affordable cost and gross takeoff weight (GTOW) of less than or equal to 10 grams.*
- ***Applications of MAVs:***
  - ***Militaristic Applications***
  - ***Surveillance***
  - ***Chemical/Radiation Detection***
  - ***Rescue and Life Detection***



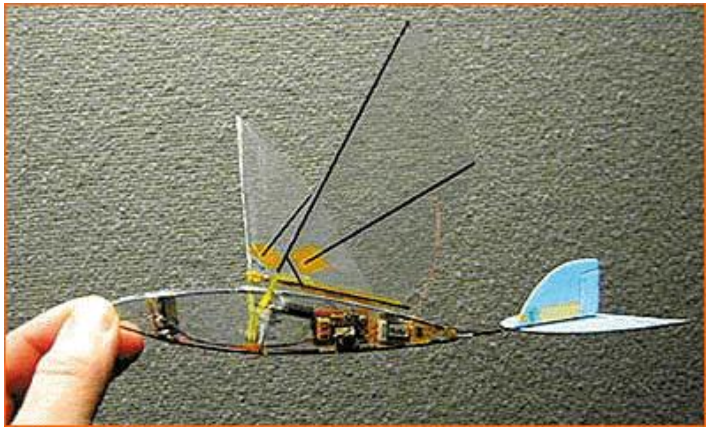
A flying robot developed by Harvard University



Fixed-Wing MAV design



Rotary-Wing MAV design

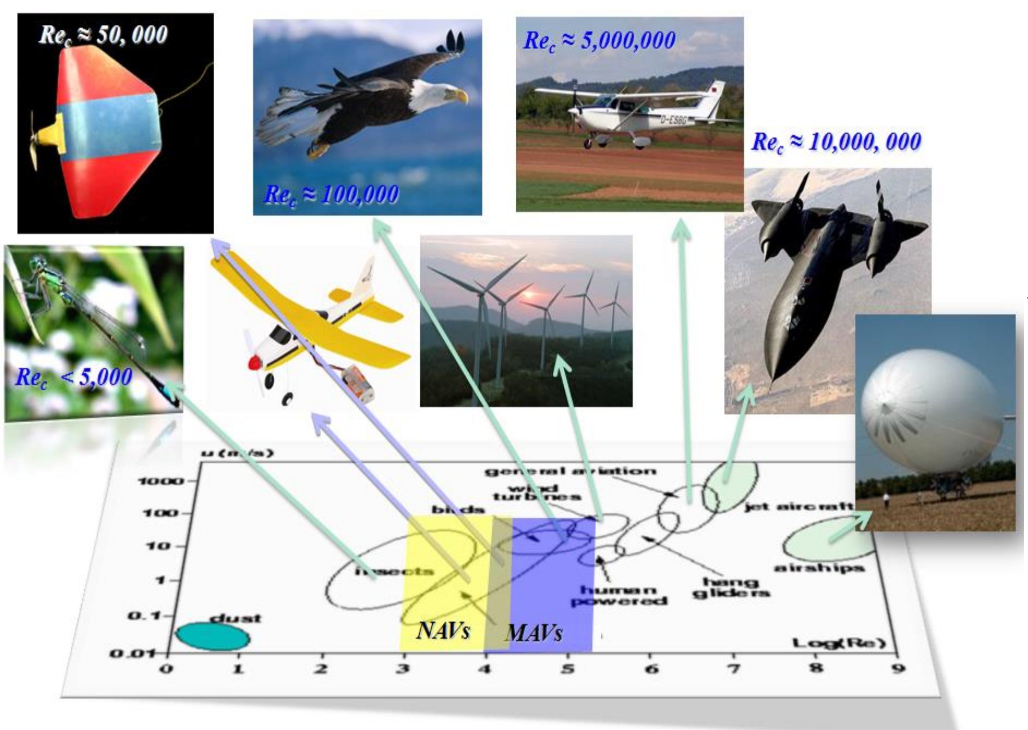


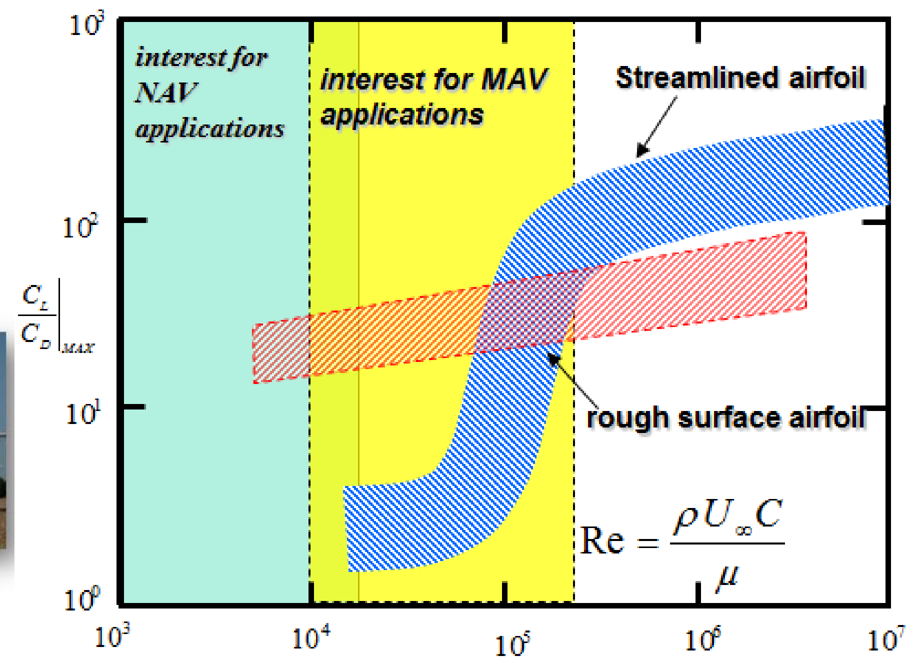
Flapping-Wing MAV design

AFRL Video about MAV

❑ Aerodynamics of Micro-Air-Vehicles (MAVs)

- *"Scale-down" of conventional airfoils could not provide sufficient aerodynamic performance for MAV applications.*
- *It is very necessary and important to establish novel airfoil shape and wing planform design paradigms for MAVs or NAVs in order to achieve superb aerodynamic performances to improve their flight agility and versatility.*

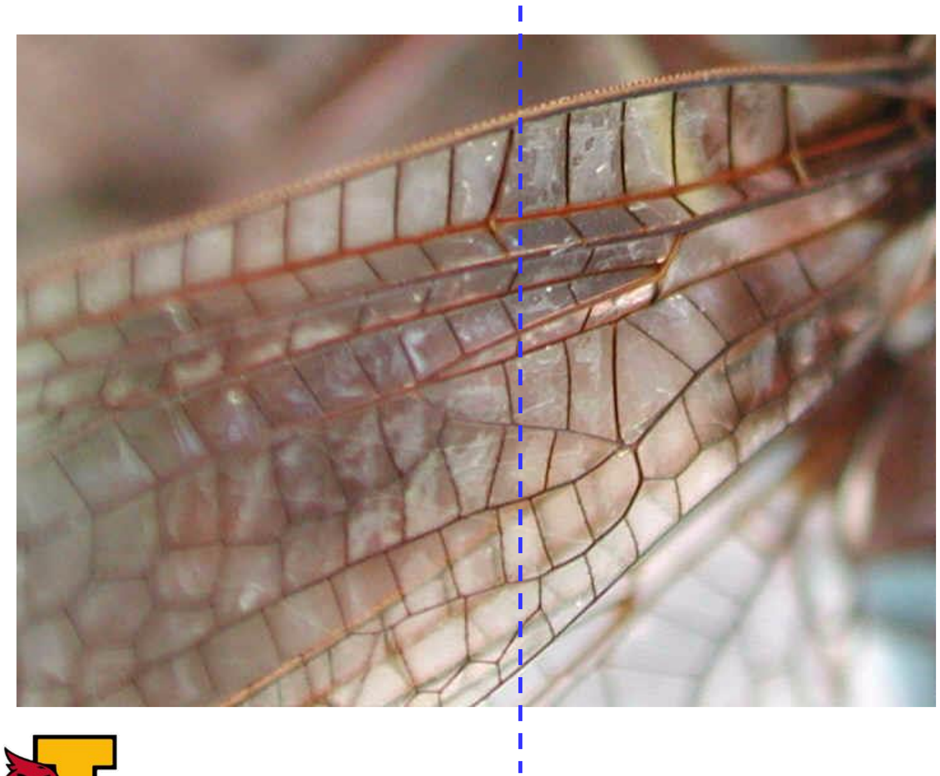


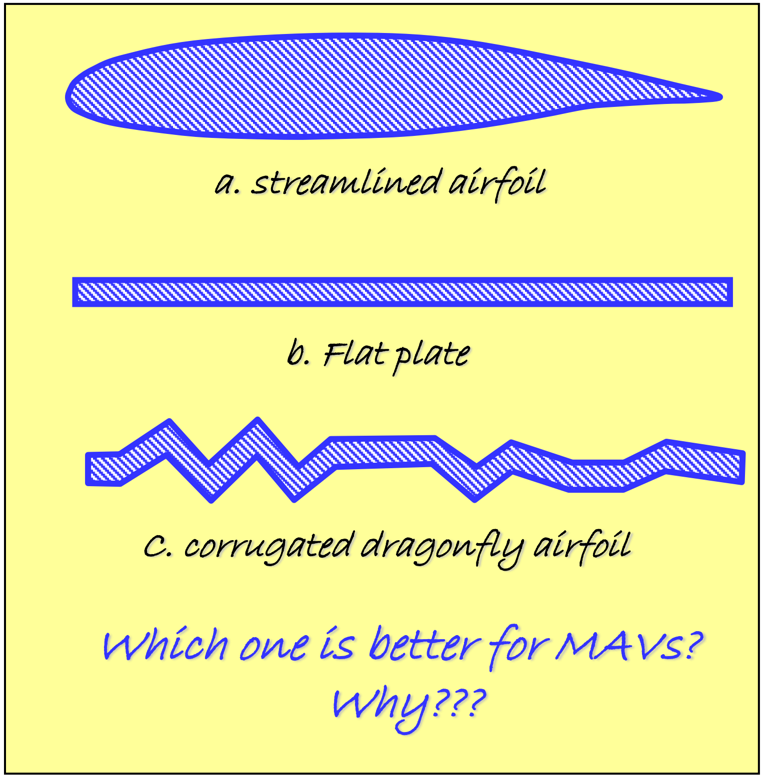


(from McMaster and Henderson, 1980)

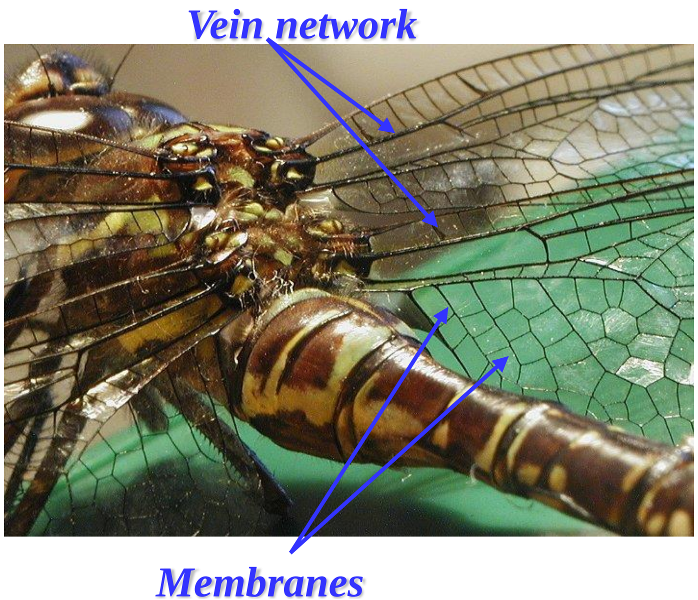
$$Re = \rho UL/\mu$$

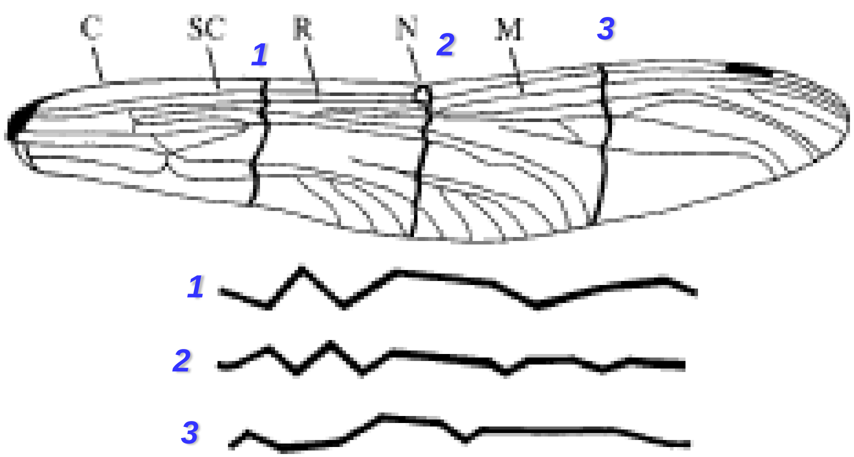
❑ Topic #1: An Experimental Study of a Bio-inspired Corrugated Airfoil at Low Reynolds Numbers



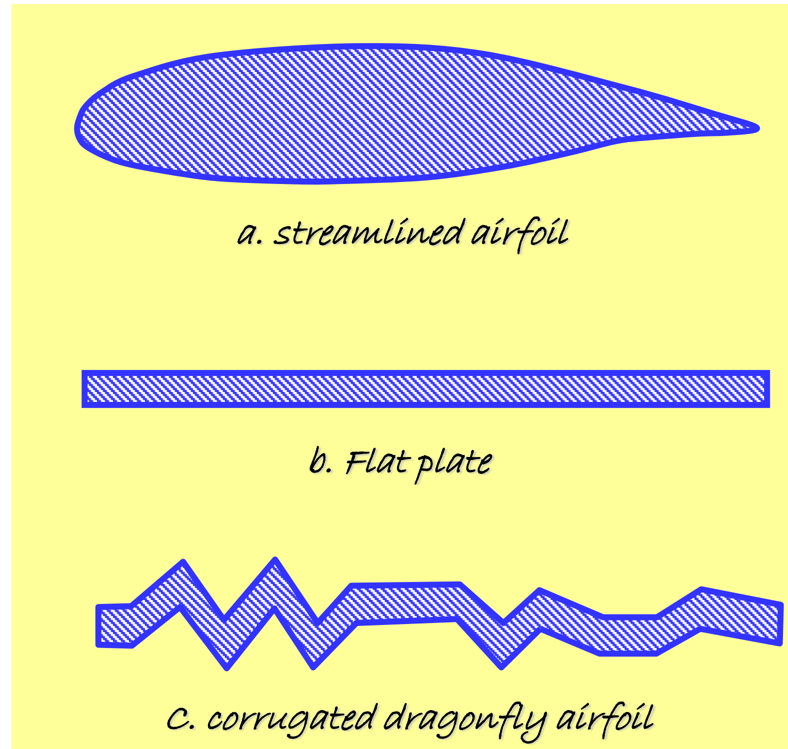


Bio-inspired Corrugated Airfoil for MAV Applications



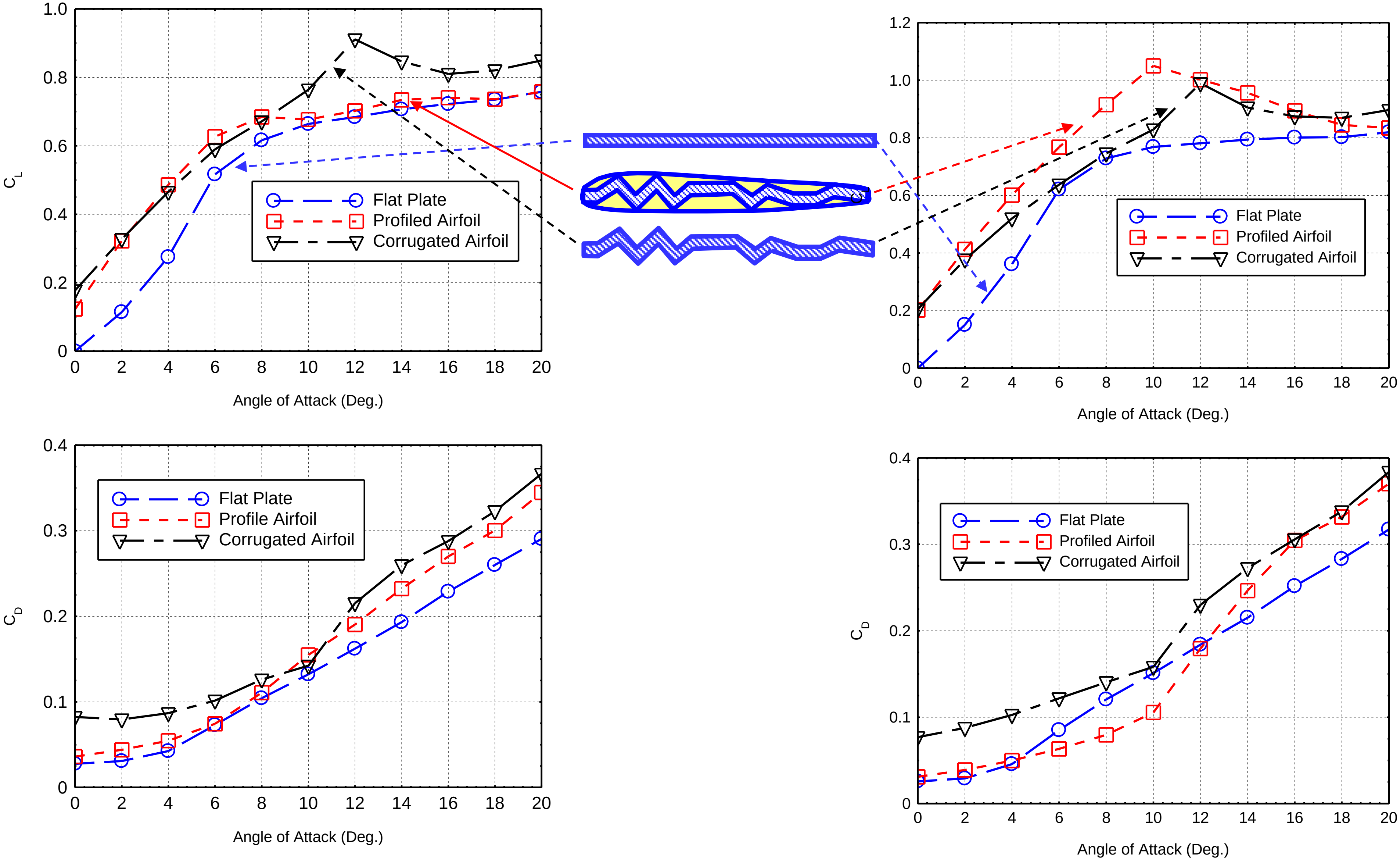


Profiles taken from Kesel, A. B., Journal of Experimental Biology, Vol. 203, 2000, pp. 3125-3135



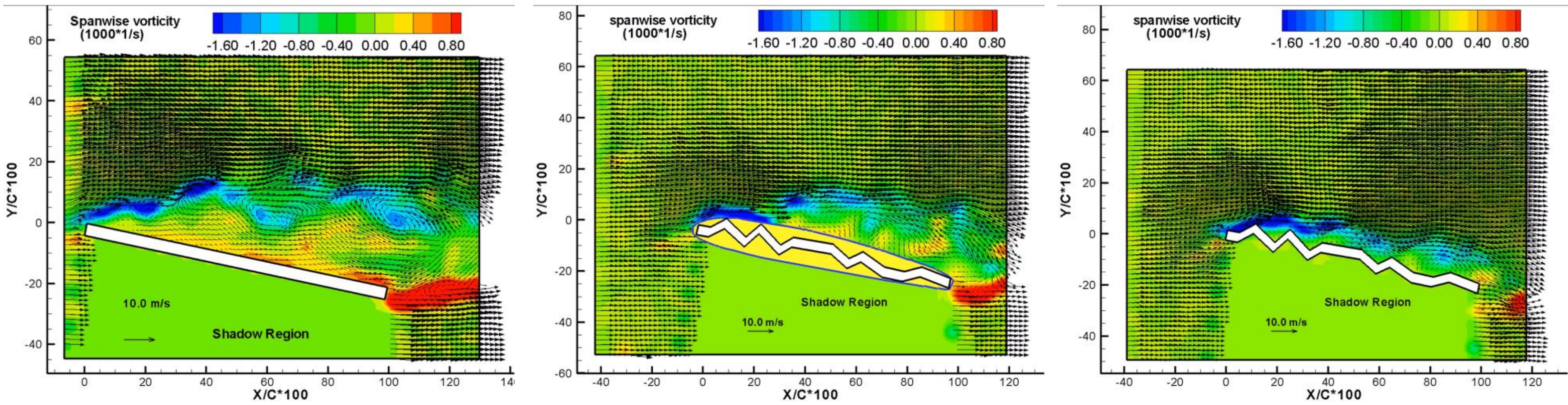
Which one is better for MAVs? Why???

Aerodynamic Force Measurement Results

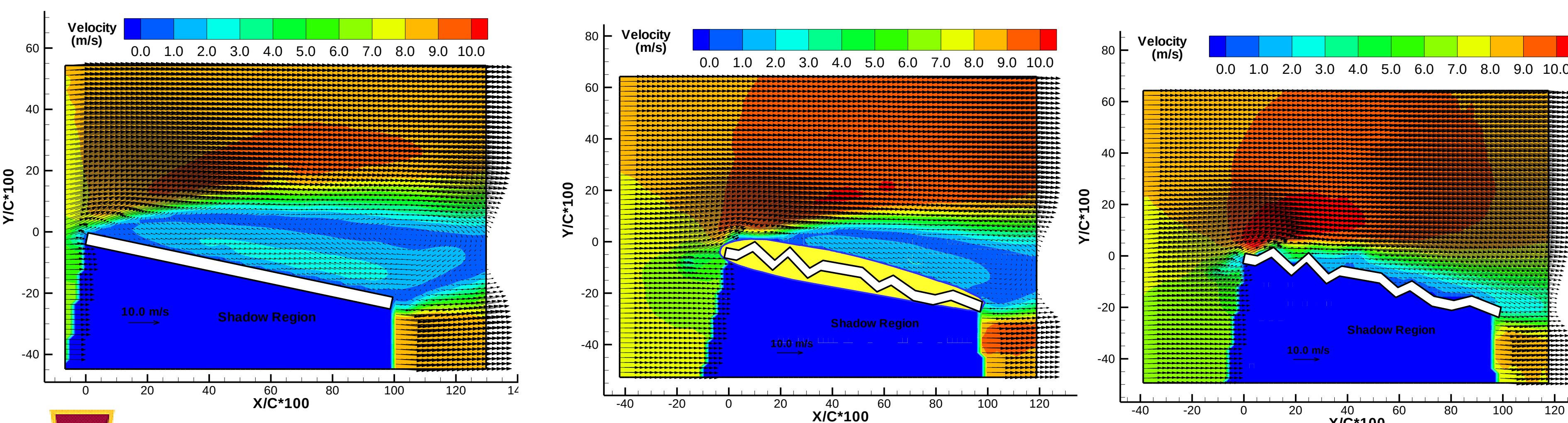


Re=50,000 *(Murphy and Hu, 2010, Experiments in Fluids)* **Re=125,000**

❑ PIV Measurement Results (AOA = 12.0 deg., Re=58,000)

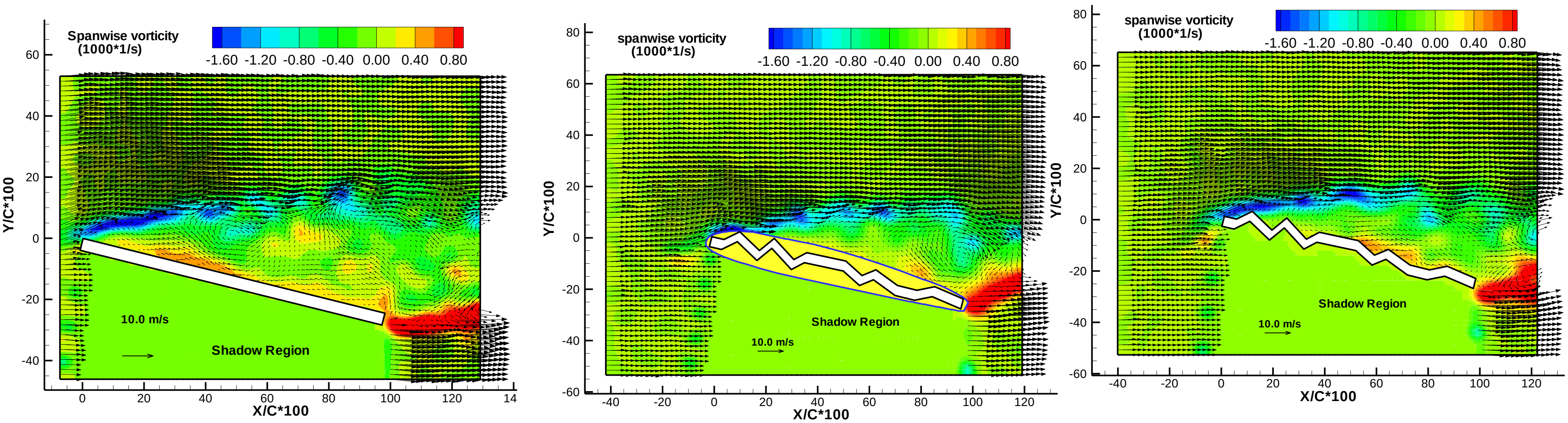


A. instantaneous results

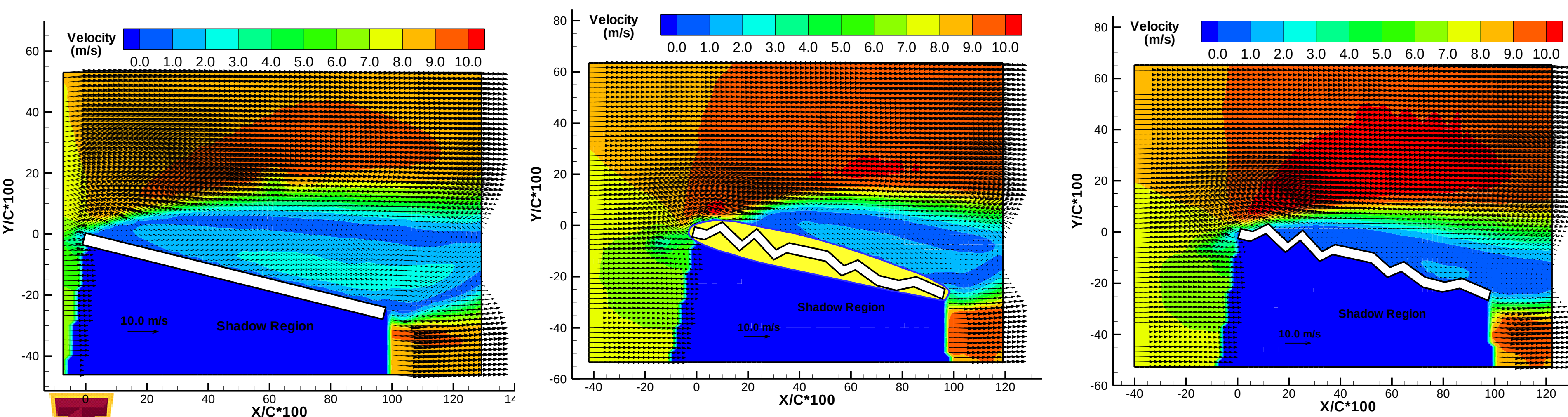


B. ensemble-averaged results

❑ PIV Measurement Results (AOA = 14.0 deg. , Re=58,000)

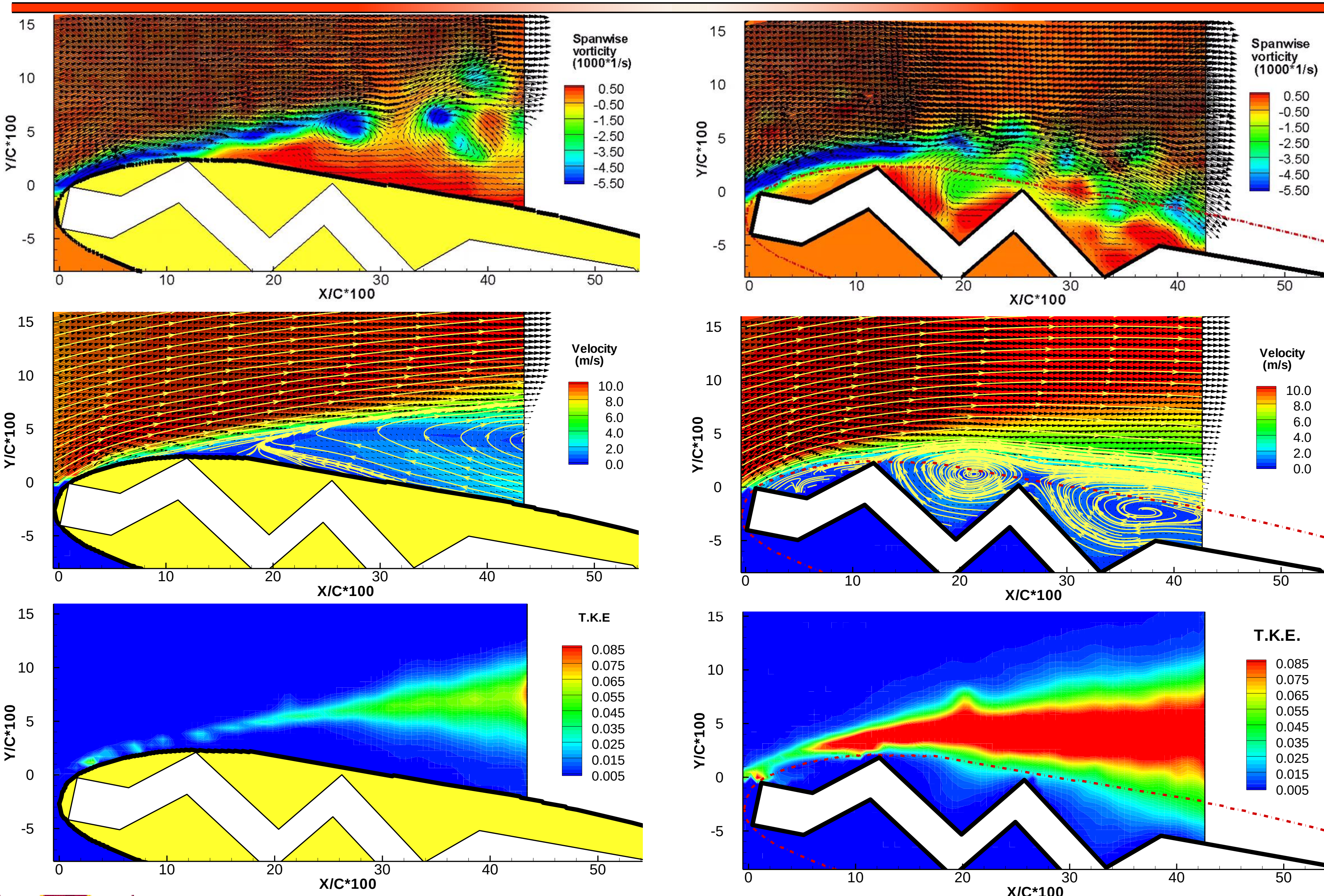


A. instantaneous results

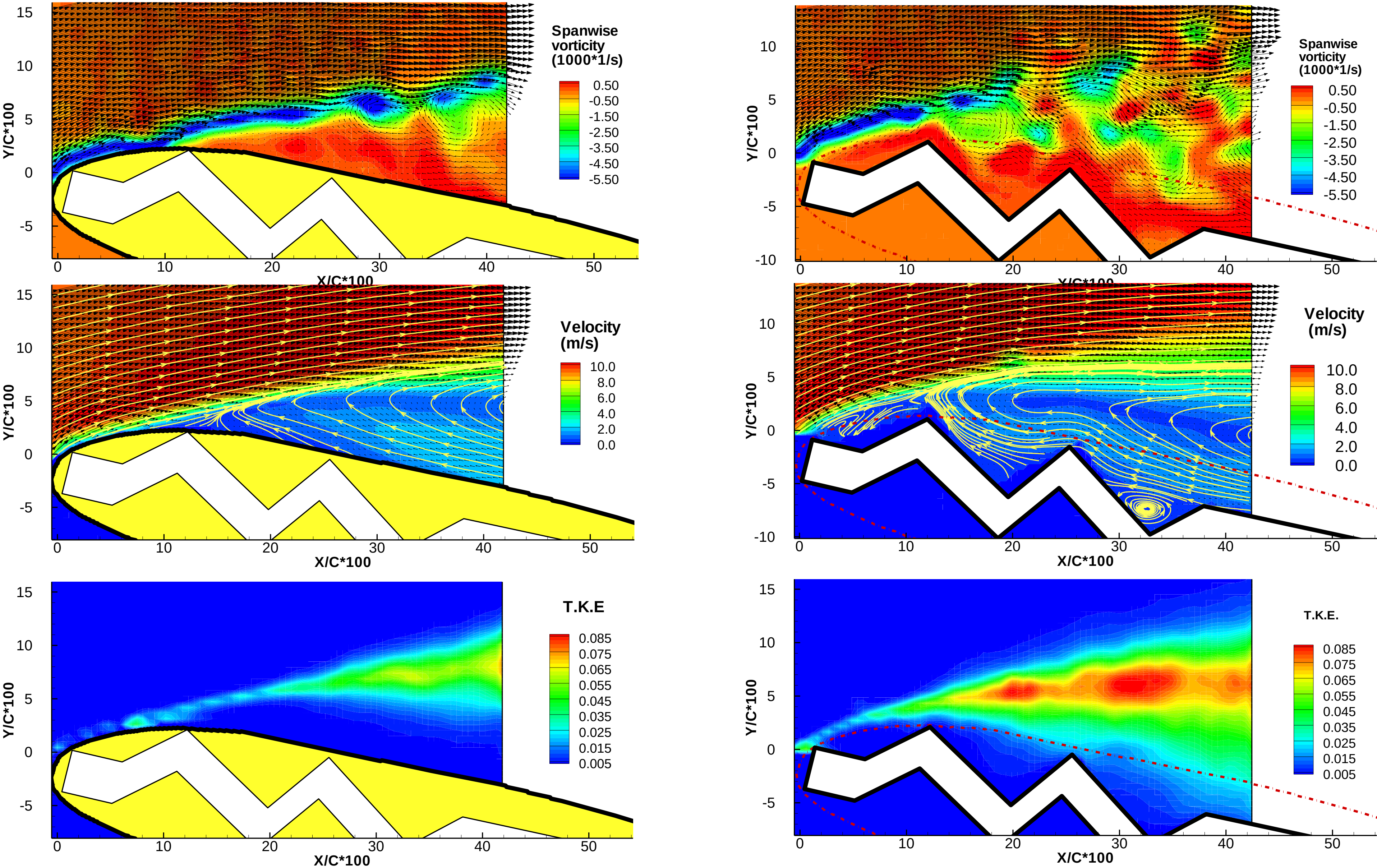


B. ensemble-averaged results

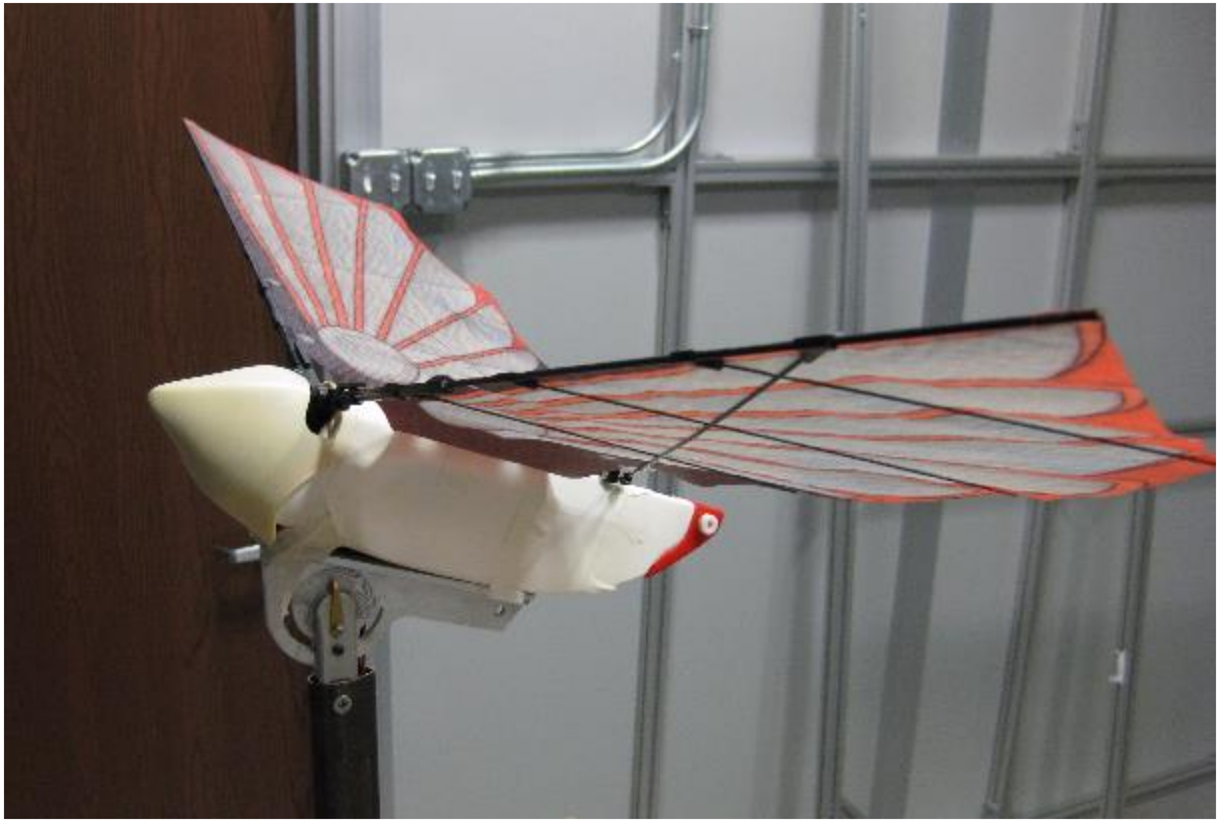
PIV Measurement Results (AOA = 12.0 deg. , Re=58,000)



PIV Measurement Results (AOA = 14.0 deg., Re=58,000)



Topic #3: An Experimental Study of Membrane Wings for Flapping-Wing MAV Applications

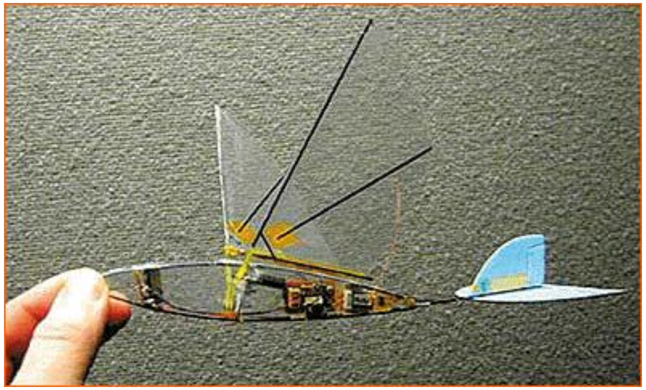


❑ Flapping Flight: the Best Choice for In-door Flight Applications

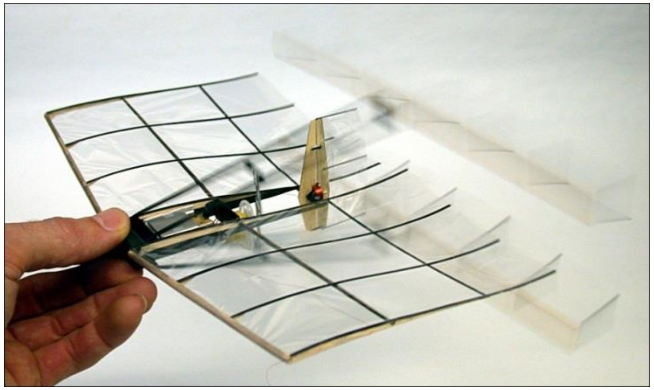
- *Flapping flight is one of the most complex yet widespread modes of transportation found in nature .*
- *Flapping flight has undoubtedly been a sophisticated realm of flight and has intrigued human beings for hundreds of years.*
- *Flapping flight seems to be the best choice for in-door Micro-Air-Vehicle (MAV) applications.*
  - *Fixed-wing MAVs do not have the required agility for obstacle-avoidance in indoor flight, and are incapable of hovering.*
  - *Rotary-wing MAVs suffer from wall-proximity effects, and are too noisy and usually inefficient for low Reynolds number flight.*

The Objectives of the Present Study

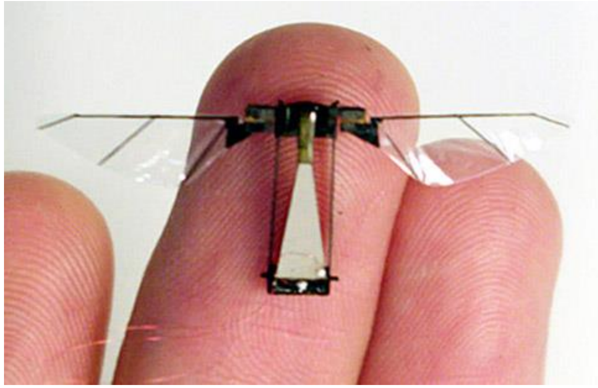
- To further our understanding about flapping flight for MAV design
  - To assess the aerodynamic benefits of flapping flight compared to soaring flight.
  - To quantify aerodynamic force generation (i.e., lift and thrust) due to flapping motion as functions of flapping frequency, forward flight speed, and orientation angle of the flapping plane with respect to the incoming flow.
- To quantify skin flexibility (rigidity) of the tested wings on their aerodynamic performances for soaring flight and flapping flight applications.



MicroBat developed by Aerovironment and Caltech



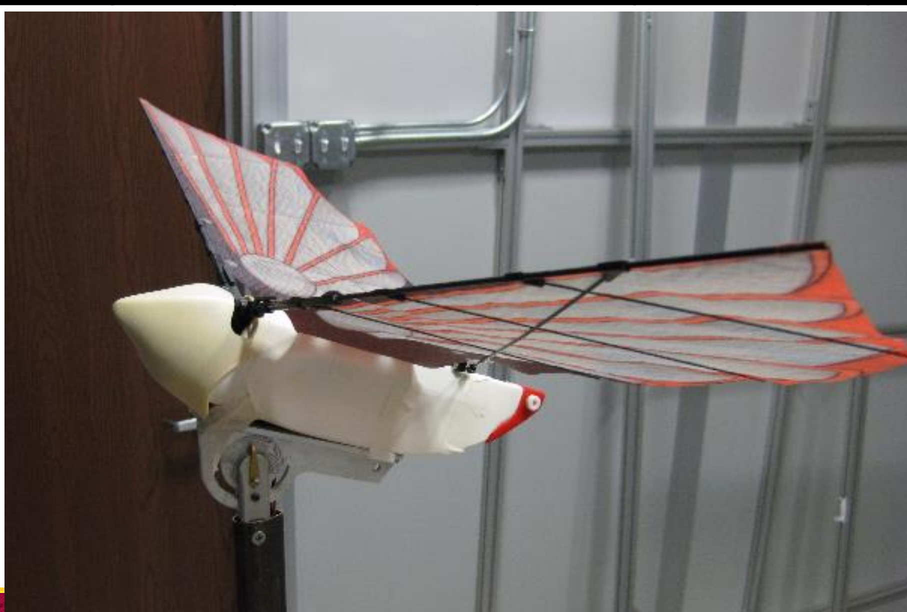
K. Jones @ Naval Postgraduate School, USA

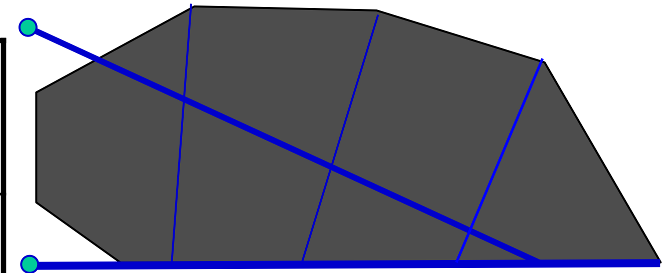


Robert Wood @Harvard

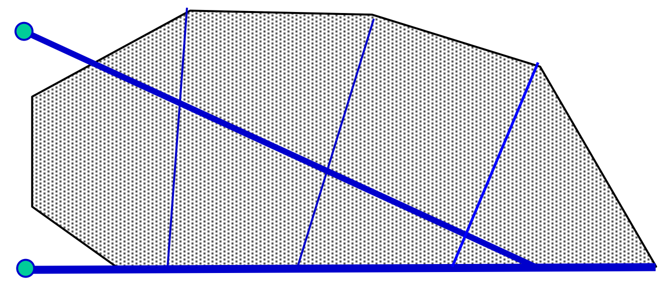
The Tested Wings

Tested Wing	*Mass (g)*	*Area of wing plateform (cm^2)*	*Wing span (cm)*	*Chrod at mid-span (cm)*	*Flapping angle (Deg.)*
Rigid wing	**60**	**475.1**	**36.8**	**16.5**	**47.4**
Nylon wing	**16**	**475.1**	**36.8**	**16.5**	**47.4**
Latex wing	**30**	**475.1**	**36.8**	**16.5**	**47.4**

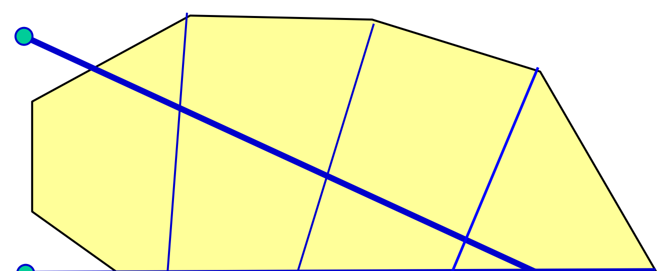




A. Conventional rigid wing - Wood Wing as the baseline for comparison



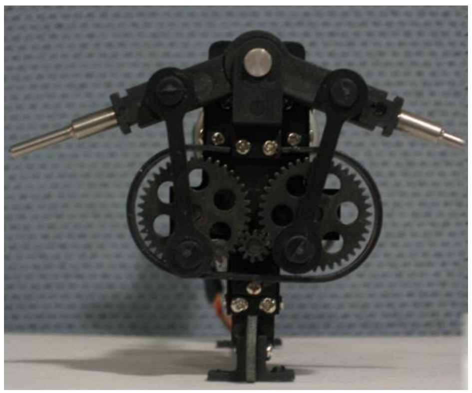
B. Flexible membrane wing #1 - Nylon Wing

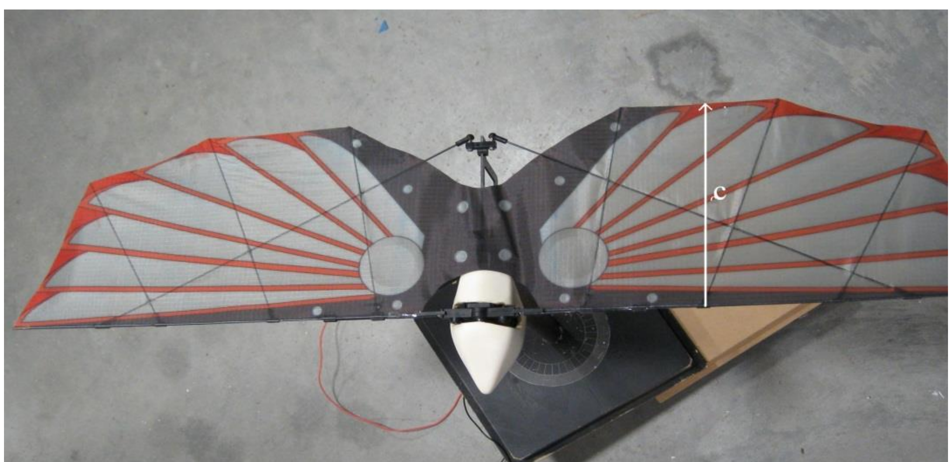


C. Flexible membrane wing #2 - Latex wing

❑ Flapping Mechanism

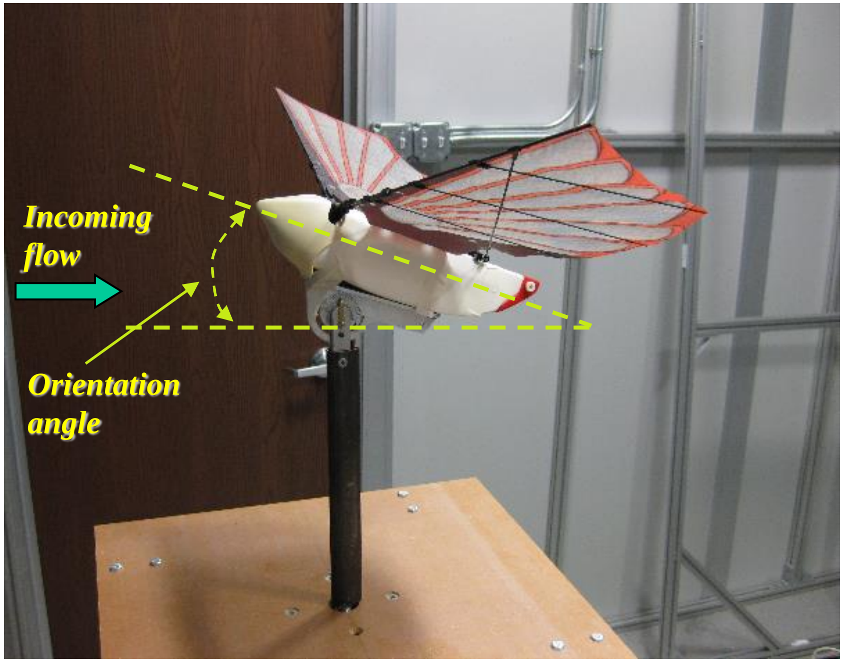
- *For the present study, parts from a Cybird P1 manufactured by NEUROS Corp. were used as the mechanism to generate the flapping motion and the wing configuration platform.*





Experimental Setup

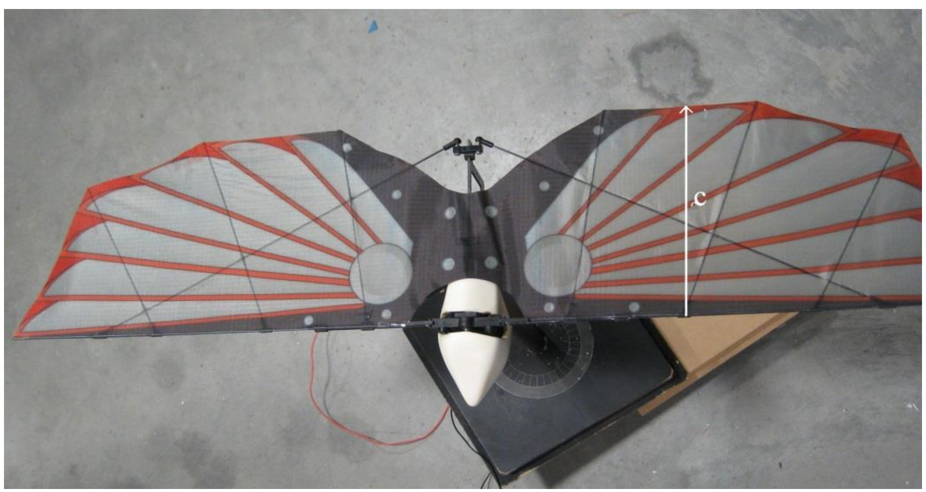
- *Orientation angle, OA= -10, -5, 0, 5, 10, 15 and 20 degrees;*
- *Incoming flow speed, V_∞= 0, 1.0, 2.0, 4,0, 6.0, 8,0 and 10.0 m/s.*
- *A 6-component load cell (JR3) was used to conduct force measurements.*
- *Data acquisition: 60,000 samples with data sample rate of 1,000 Hz for each case.*
- *Chord Reynolds numbers: Re_c = 10,000 ~ 100,000.*

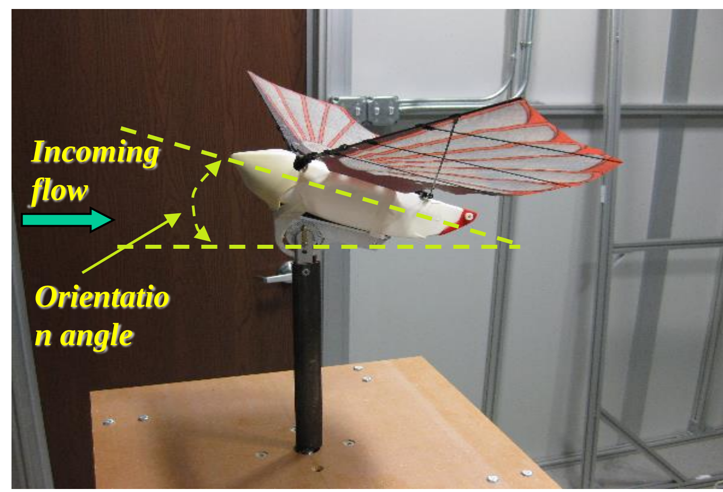


AFRL Low-speed wind tunnel at UF-REEF

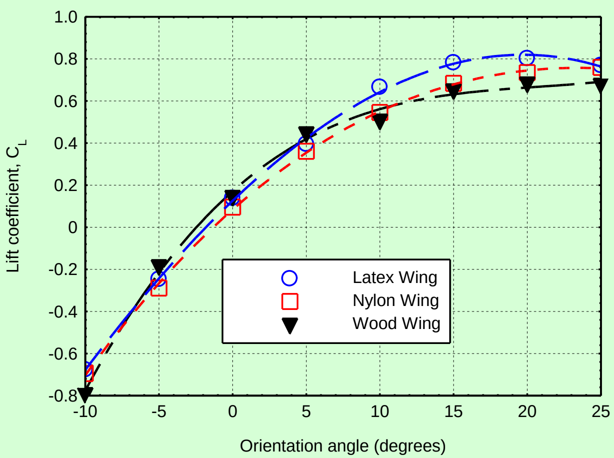
❑ Soaring Flight Experiments

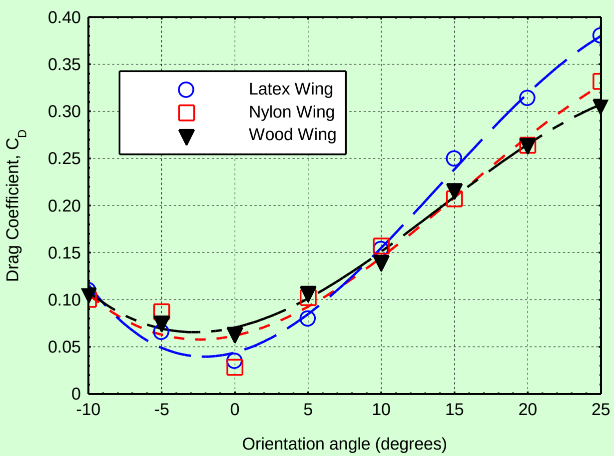
- *During the soaring flight experiments, the rigid leading edges of the tested wings were positioned horizontally.*
- *The test models were fixed wing MAVs.*
- *Incoming flow velocity in the test section (i.e., the forward flight speed) was varied from 1.0 m/s to 10.0 m/s.*
- *For soaring flight, the orientation angle (OA) is actually the angle of attack of the tested wings with respect to the incoming flows*



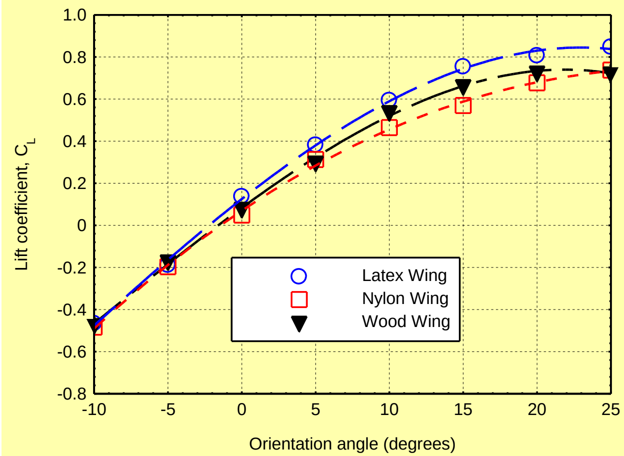


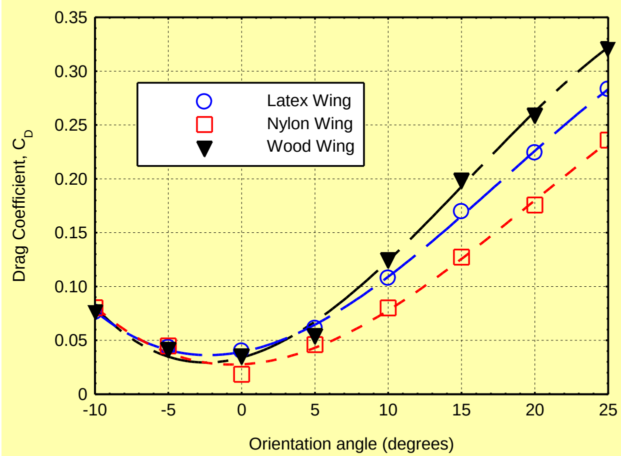
Measurement Results In Soaring Flight



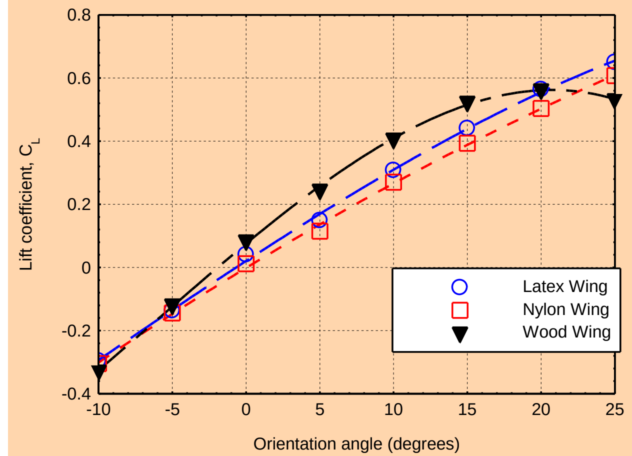


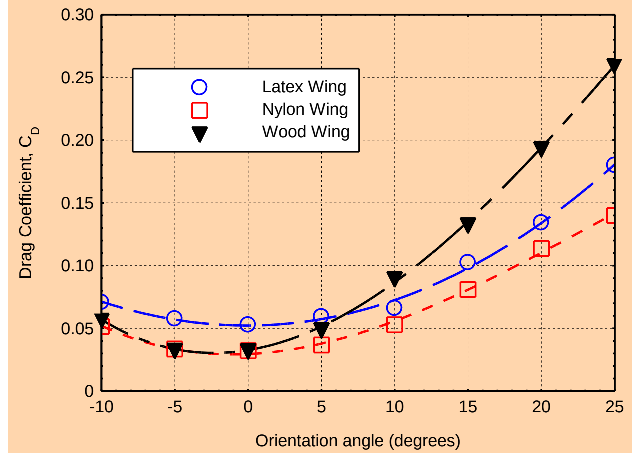
Soaring velocity V=2.0 m/s, Re_c=20,000





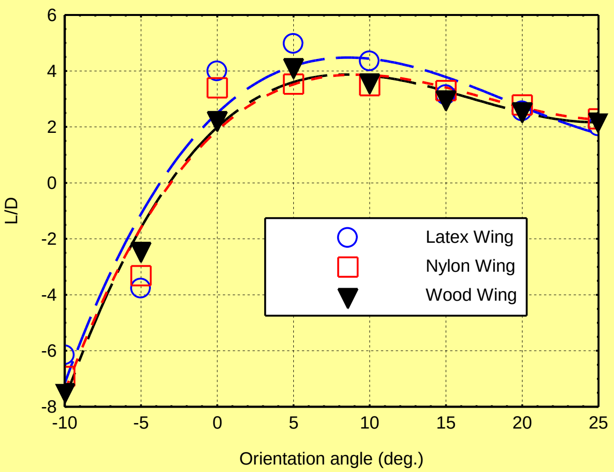
Soaring velocity V=4.0 m/s, Re_c=40,000



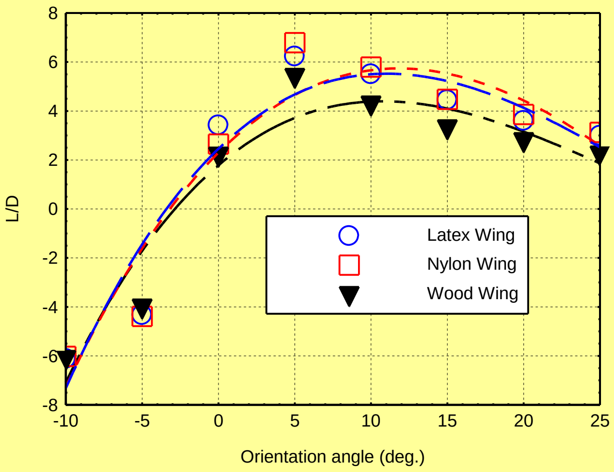


Soaring velocity V=8.0 m/s, Re_c=80,000

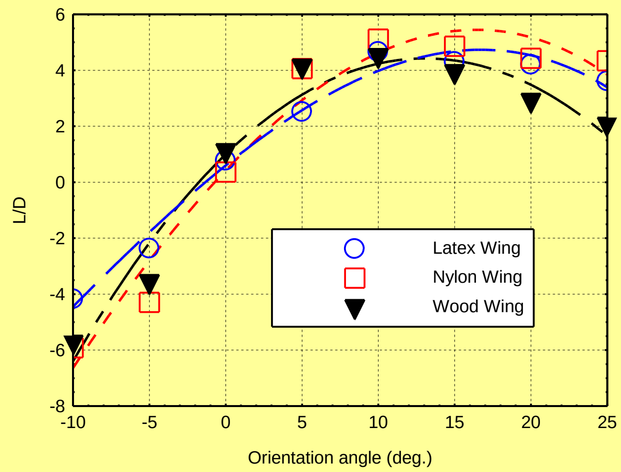
Measurement Results In Soaring Flight



Soaring velocity V=2.0 m/s, Re_c=20,000



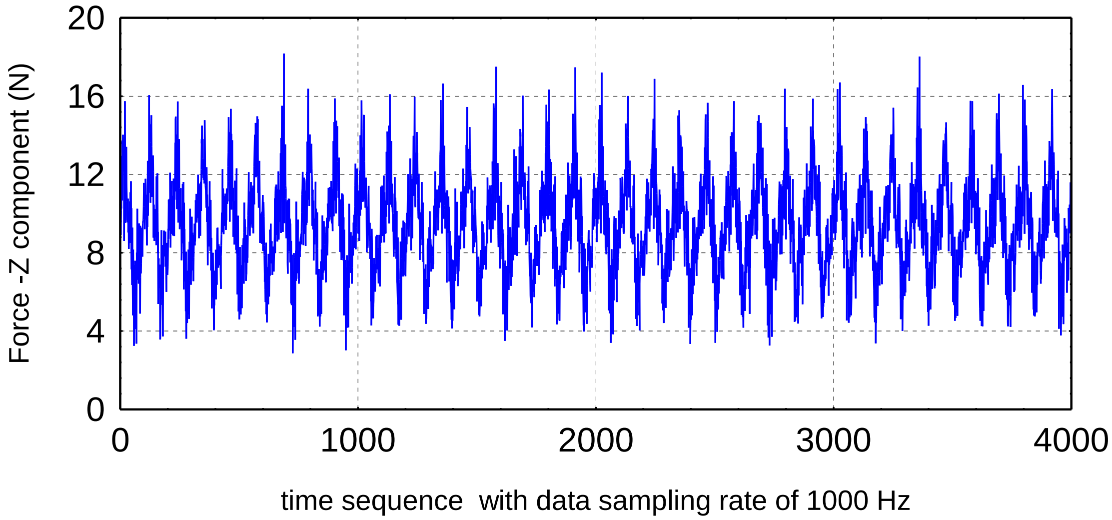
Soaring velocity V=4.0 m/s, Re_c=40,000

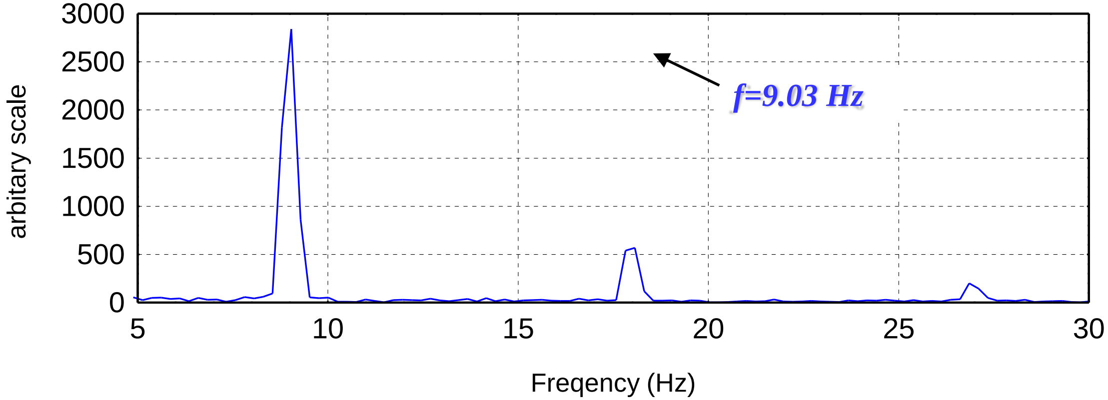


Soaring velocity V=8.0 m/s, Re_c=80,000

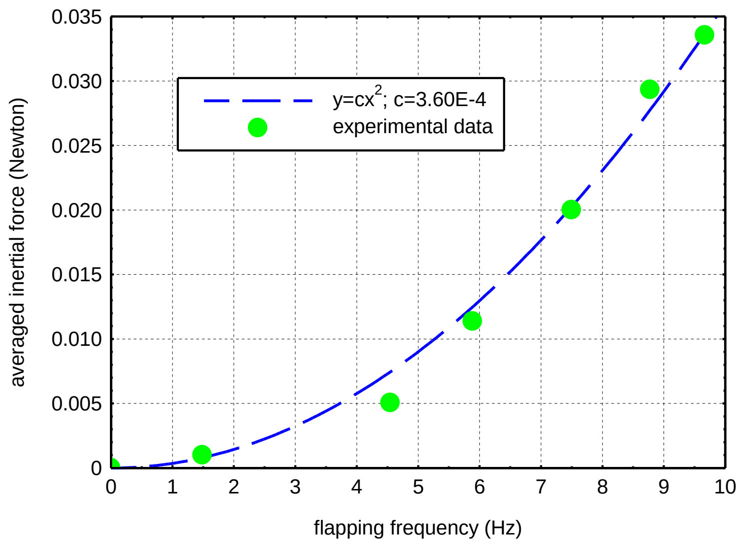
- ***Flexible membrane wings could provide better aerodynamic performance** compared with conventional rigid wing for soaring flight or fixed-wing MAV applications.*
- *The aerodynamic benefits of using flexible membrane wings for soaring flight are **highlighted for the cases with relatively high soaring speed and high angles of attack**, where the induced deformation on the flexible membrane wings become more obvious.*
- ***The nylon wing**, which is less flexible than the latex wing, was found to have the **best overall aerodynamic performance** among the three tested wings for soaring flight.*
- *It is important to **chose a proper flexibility (or rigidity)** of the membrane skins in order to achieve improved aerodynamic performance by using flexible-membrane airfoils/wings for fixed-wing MAV applications.*

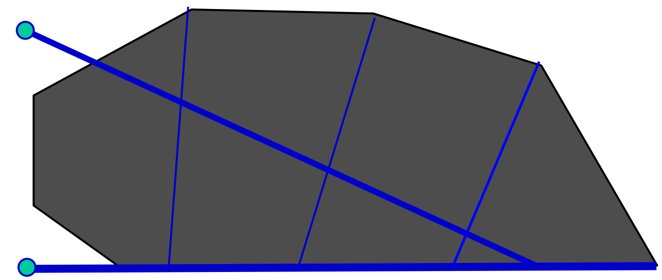
Flapping Flight Experiments



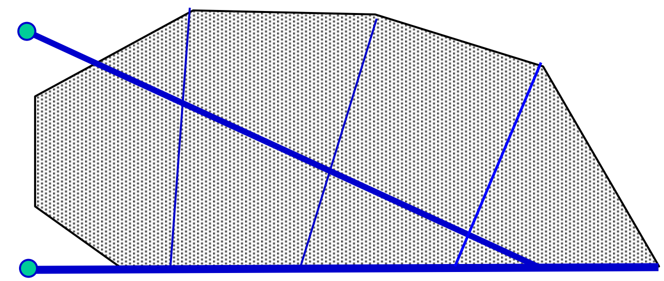


Inertial Force Corrections

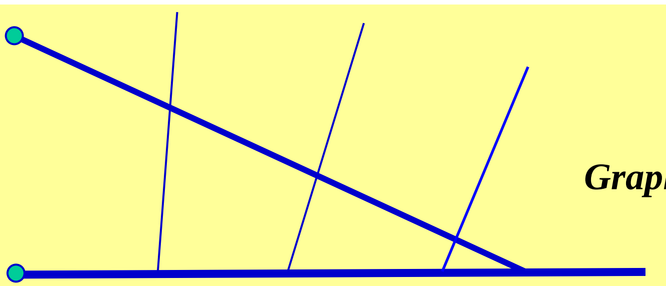




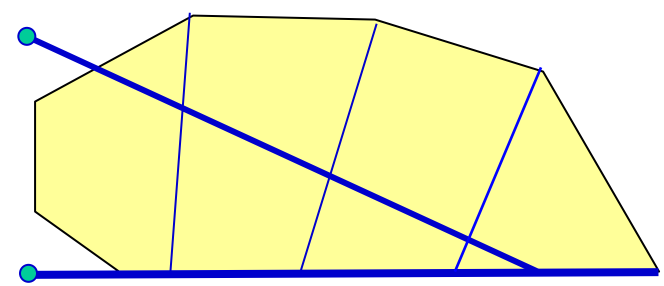
A. Rigid wings – wood (60g)



B. Nylon wing – Nylon (16g)



Graphite frame (12g)



C. Latex wings – latex (30g)

$$F_{inertial\,force} \propto mf^2$$

Characterization of Aerodynamic Performance of Flapping Flight

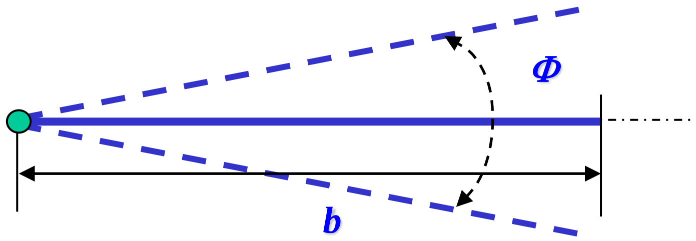
Aerodynamic benefits of flapping flight:

Thrust and lift augmentations due to flapping motion:

$$\Delta C_T = \frac{Thurst_{flapping} - Thurst_{soaring}}{\frac{1}{2}\rho V^2 S}$$

$$\Delta C_L = \frac{Lift_{flapping} - Lift_{soaring}}{\frac{1}{2}\rho V^2 S}$$

V: Incoming flow velocity / flight speed
b: wing span half length
f: wing beating frequency
Φ: wing flapping angle
S: area of wing planform



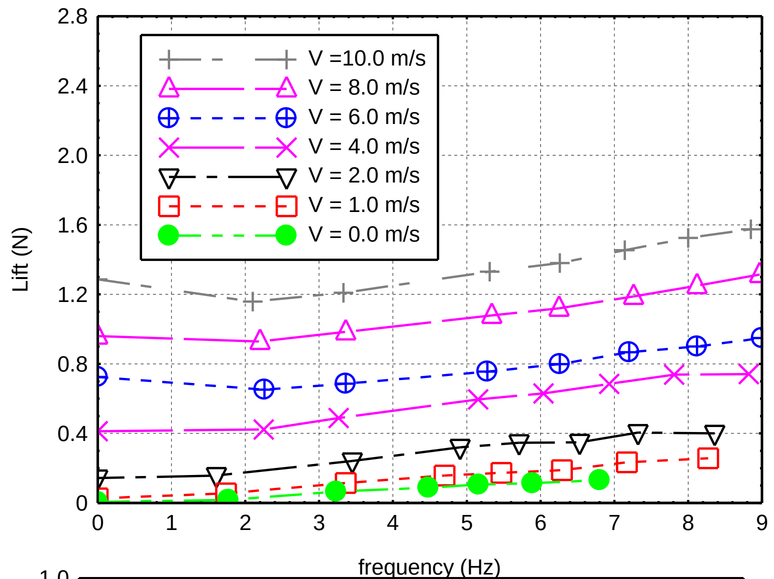
- ***Advance ratio, J :***

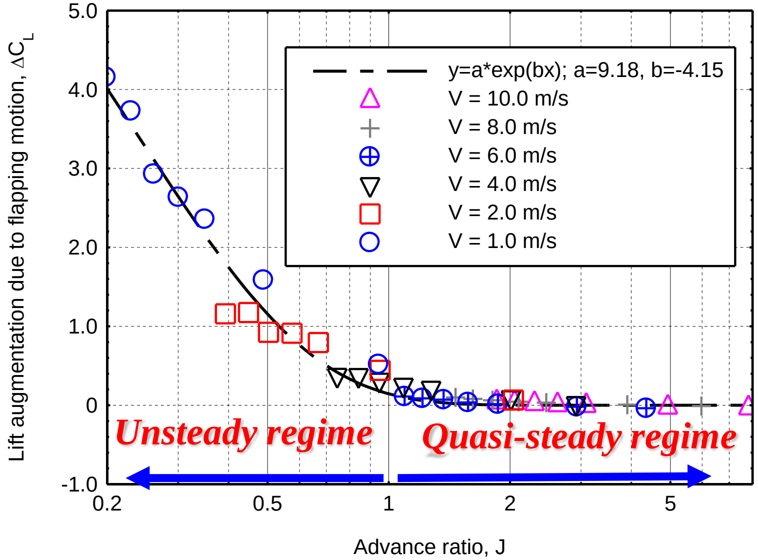
$$J = \frac{\text{Incoming flow velocity}}{\text{Wing tip velocity}} = \frac{V}{2\Phi f b}$$

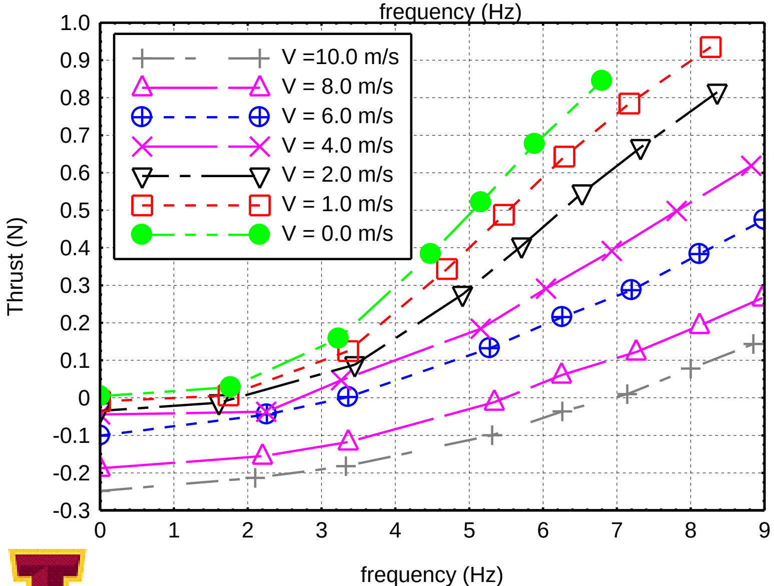
- *J >1, flapping flight in quasi-steady regime*
- *J < 1, flapping flight in unsteady regime*

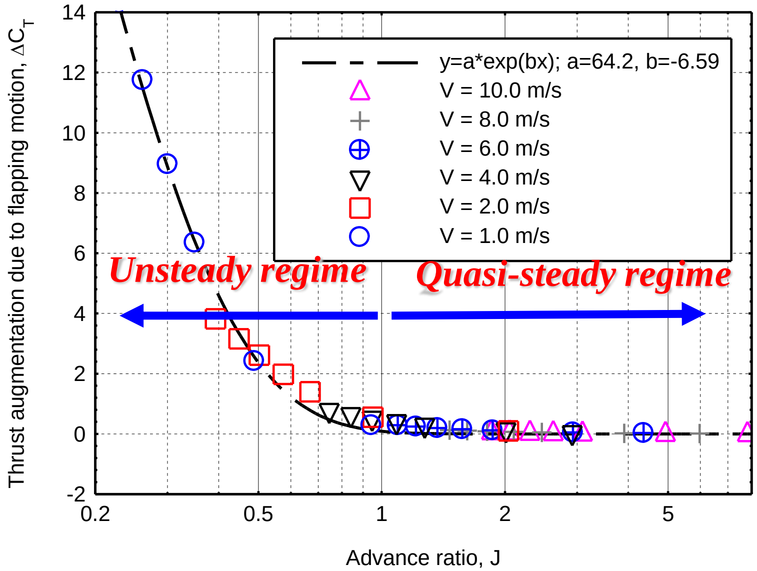
- ***The advance ratio of the bumblebee, black fly and fruit fly in free flight is 0.66, 0.50, and 0.33 respectively***

Flapping Measurement Results



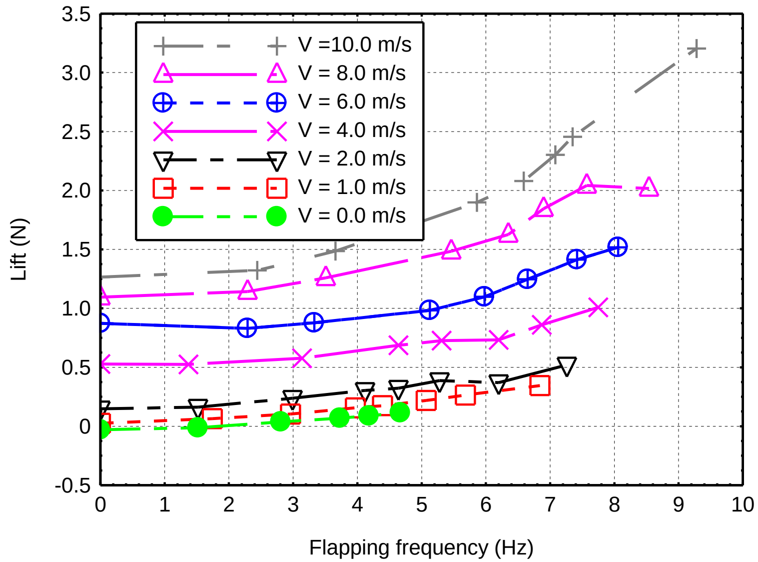


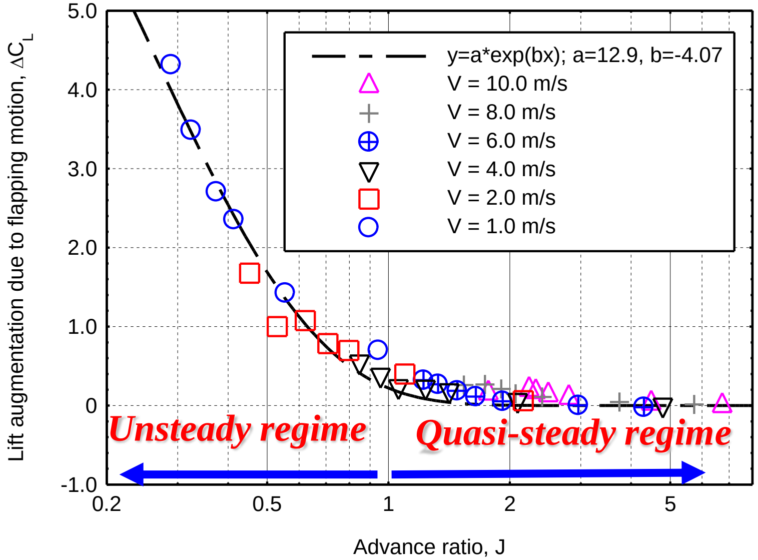


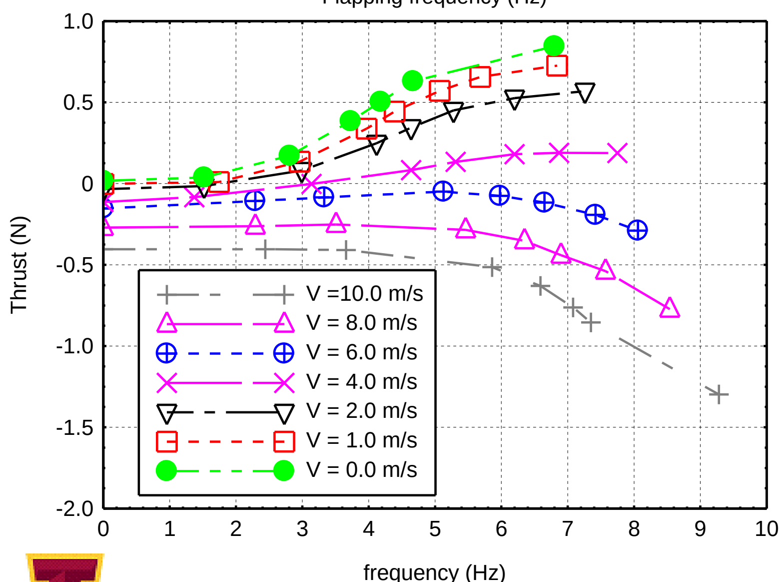


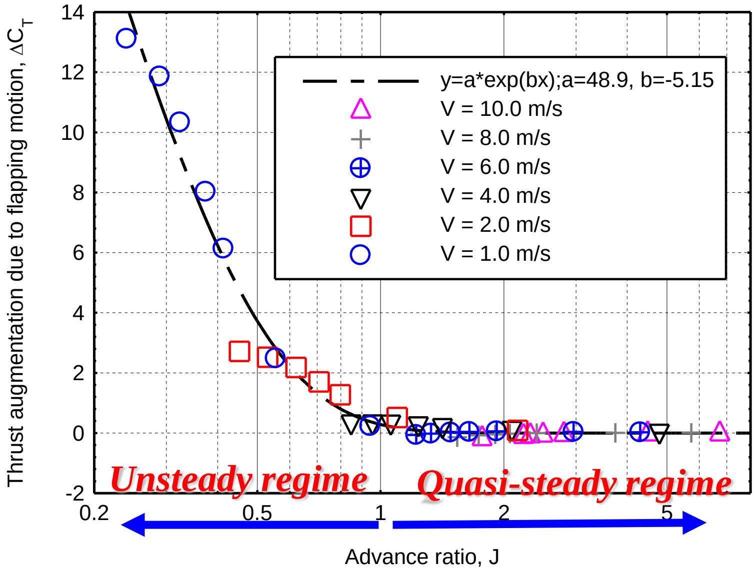
Flexible Nylon Wing, OA =10.0 deg.

Flapping Measurement Results



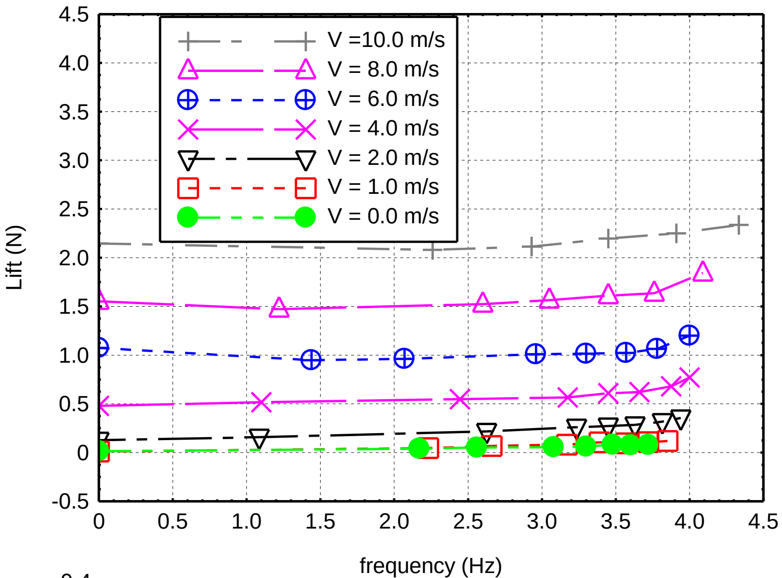


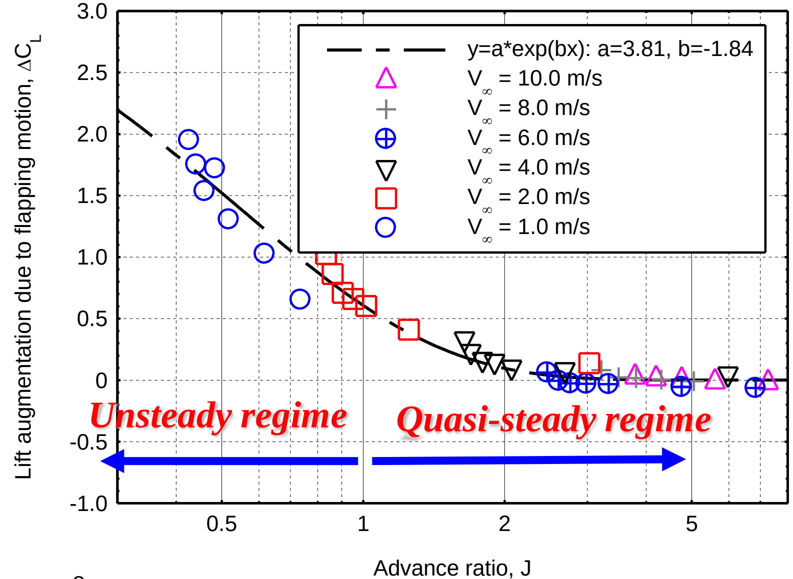


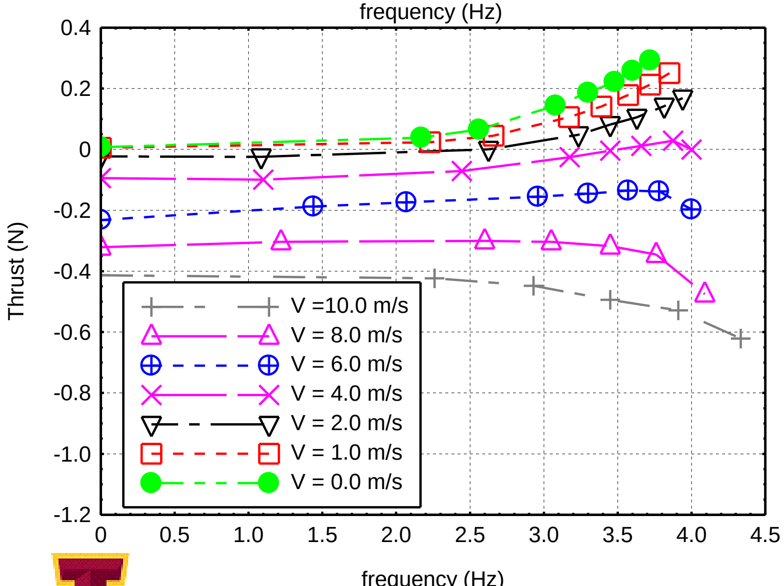


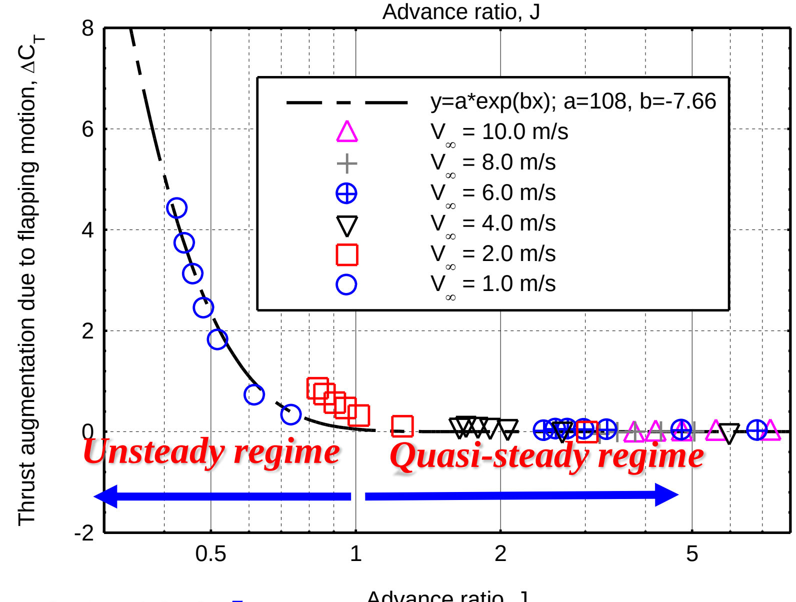
Flexible Latex wing, OA=10.0 deg.

❑ Measurement Results for Flapping Flight



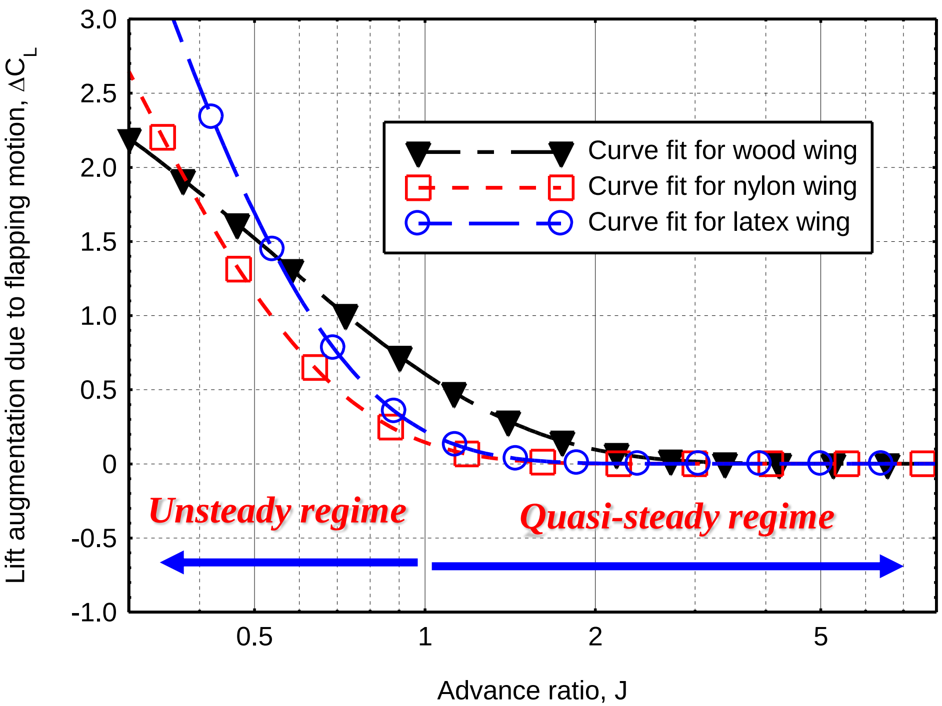




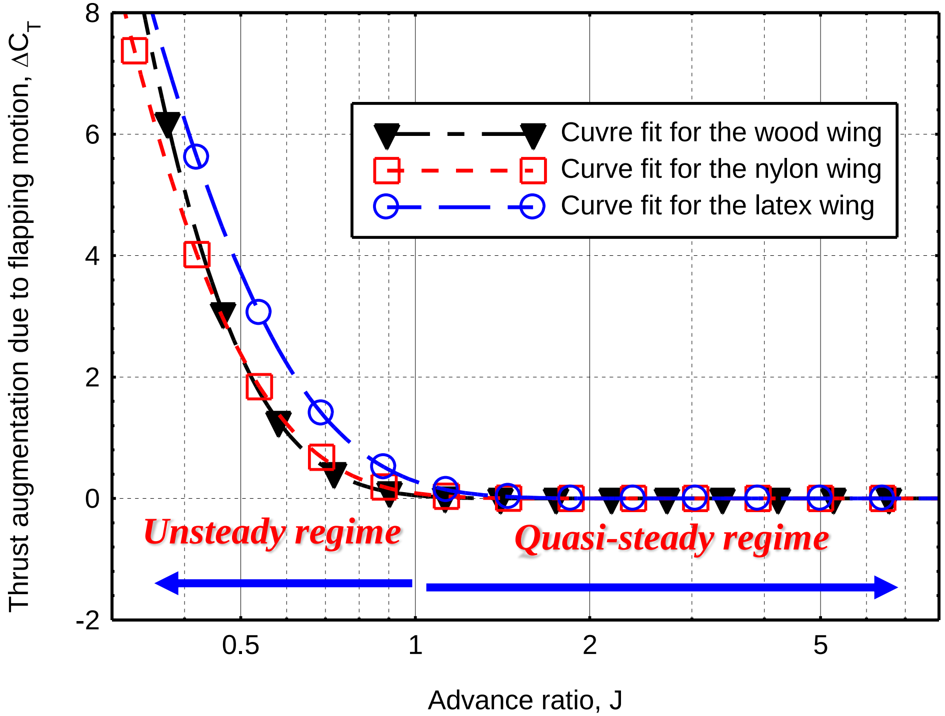


Rigid Wood Wing, OA=10.0 deg.

Comparison of the tested wings



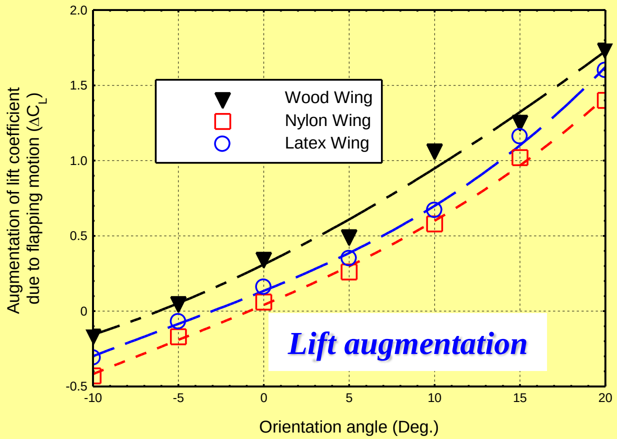
Lift augmentation

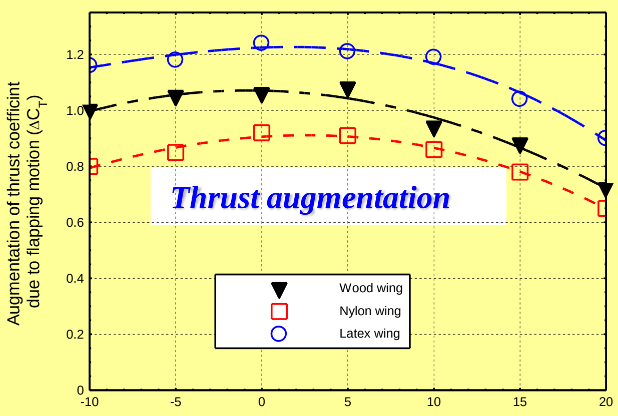


Thrust augmentation

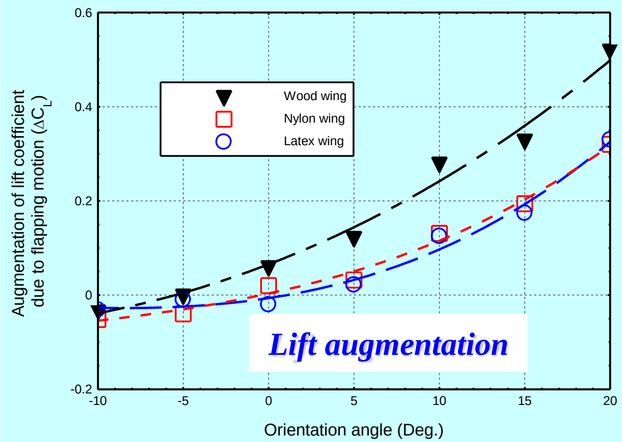
OA=10.0 deg.

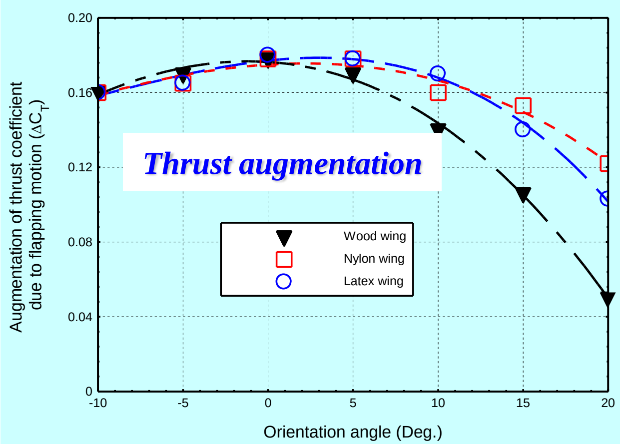
❑ Effects of the Orientation Angle



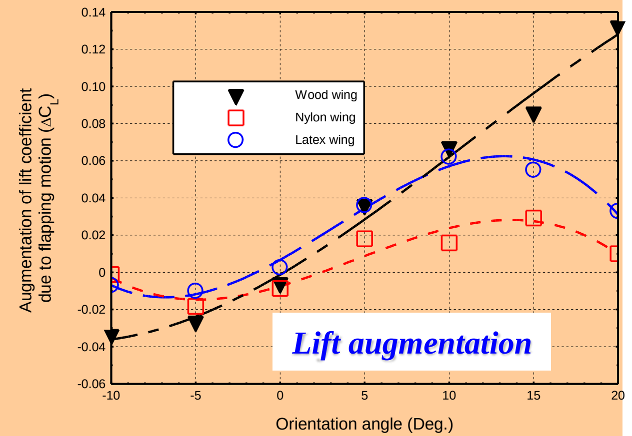


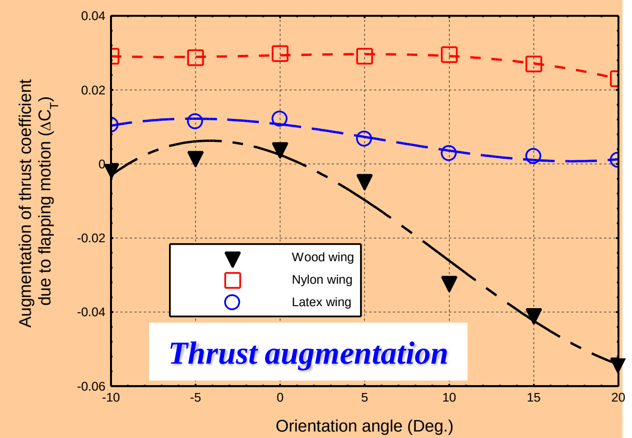
Incoming flow: ***V= 2.0 m/s***
Flapping frequency: ***f = 4.0 Hz***
Advance Ratio: ***J = 0.8***
Flapping flight in unsteady regime





Incoming flow: ***V= 4.0 m/s***
Flapping frequency: ***f = 4.0 Hz***
Advance Ratio: ***J = 1.6***
Flapping flight in quasi-steady regime

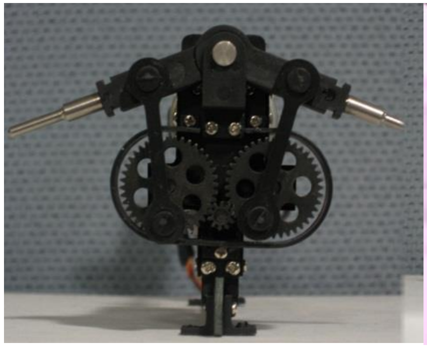




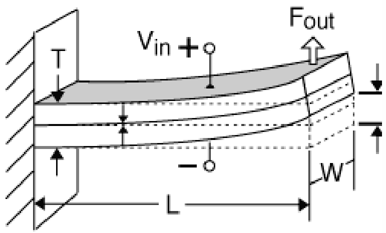
Incoming flow: ***V= 8.0 m/s***
Flapping frequency: ***f = 4.0 Hz***
Advance Ratio: ***J = 3.2***
Flapping flight in quasi-steady regime

❑ Topic #4: Unsteady Vortex Structures in the Wake of a Piezoelectric Flapping Wing

❑ Flapping Mechanism for Flapping Wing MAVs and NAVs




- *Mechanical flapping mechanism*
  - *Bulky in size*
  - *Structure complex*
  - *Relatively low flapping frequency f < 15 Hz*

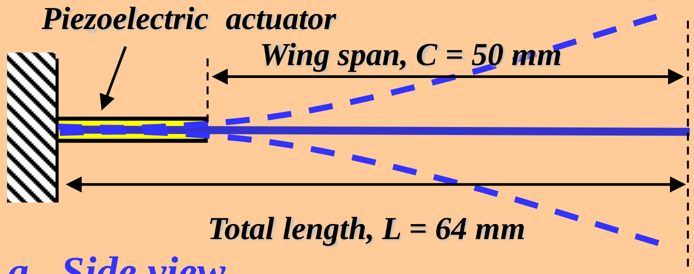


Piezoelectric actuator

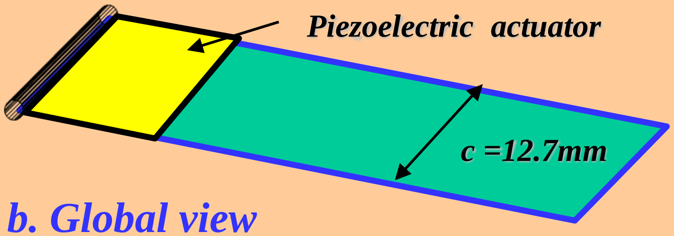
- *Piezoelectric actuator–based flapping Mechanism*
  - *Compact in size*
  - *Simple structure*
  - *Much higher flapping frequency , f= 60~200Hz*

Fruit fly @50 ~ 150Hz

Dragonfly @ 30 ~ 100 Hz

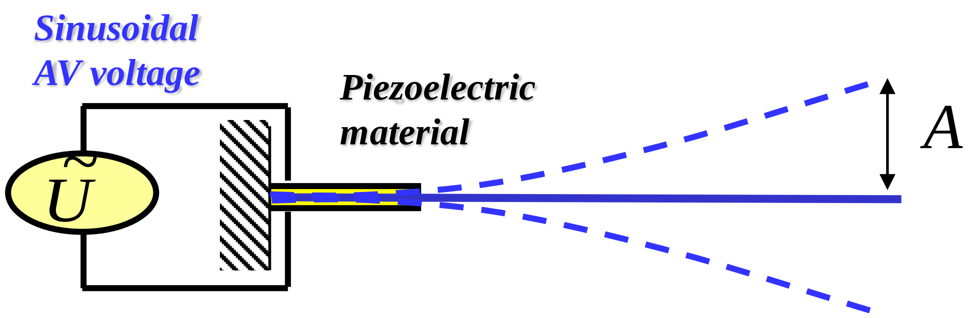


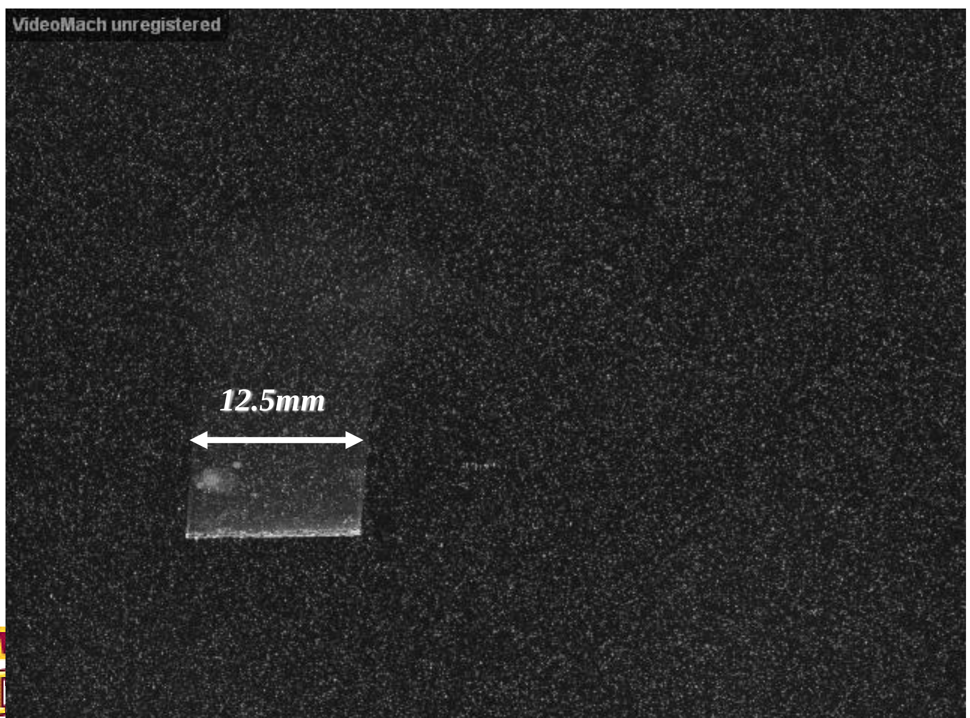
a. Side view

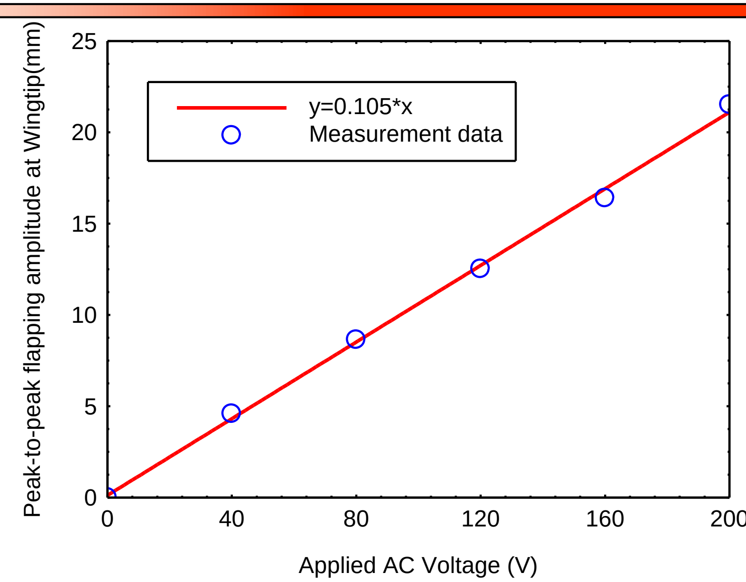


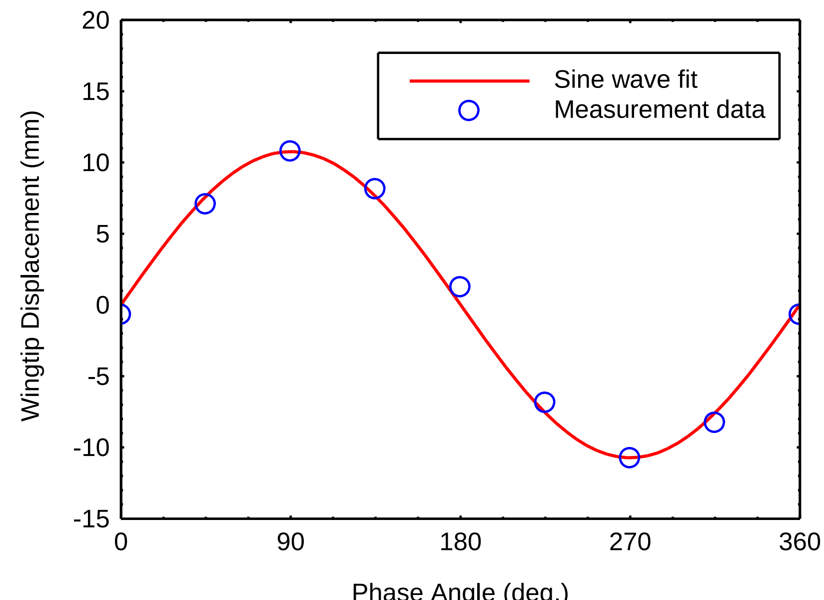
b. Global view

Dynamic Response of a Piezoelectric Flapping Wing

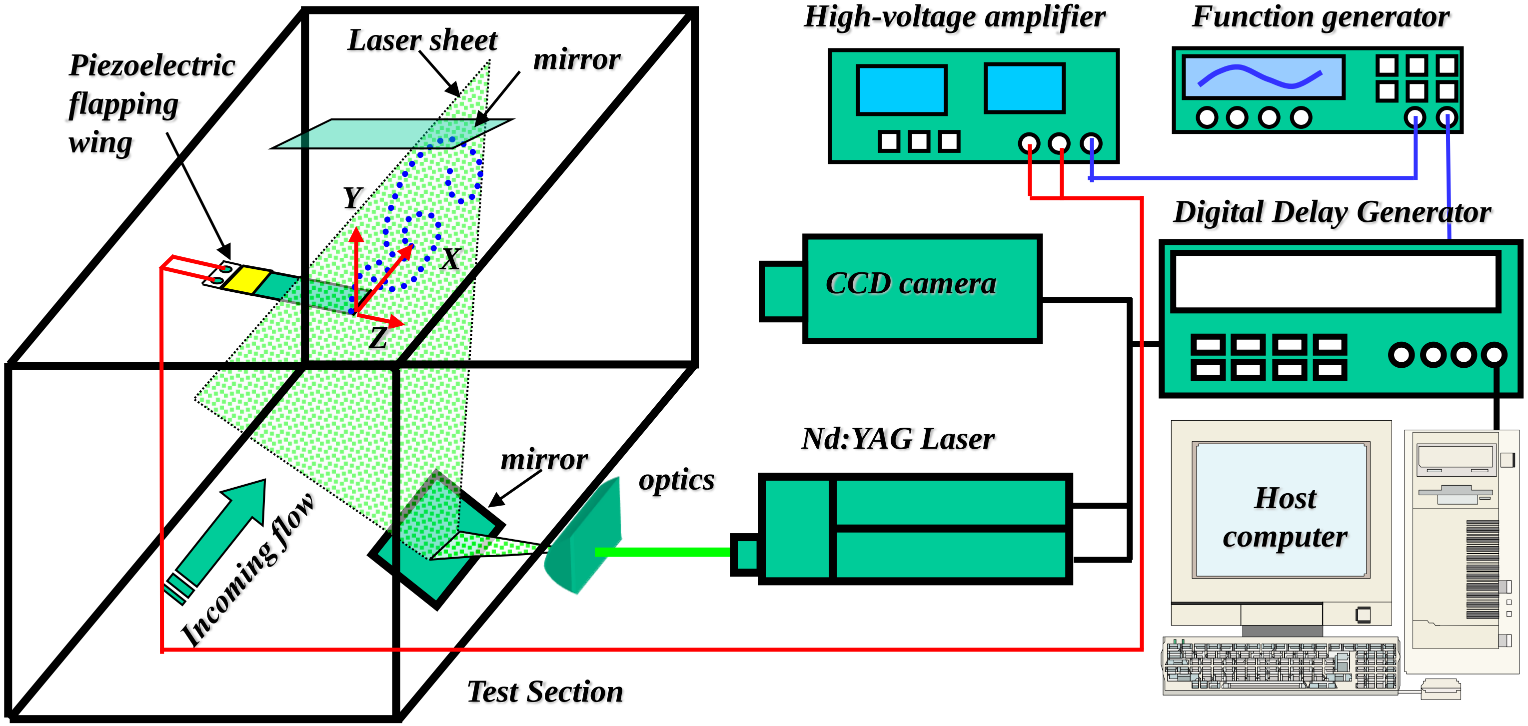


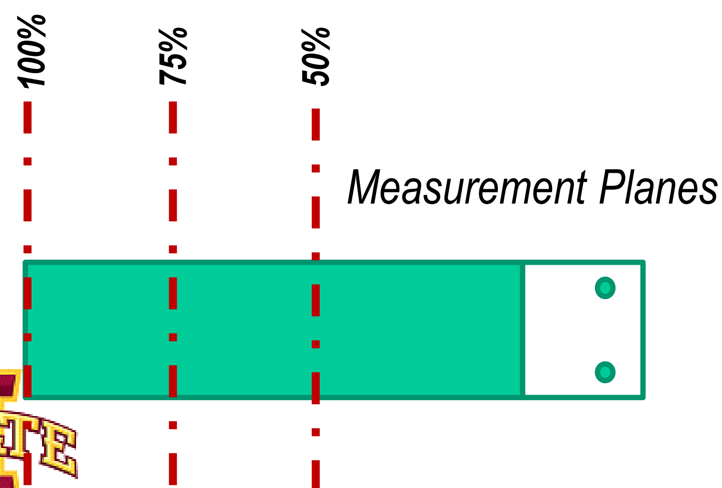






Experimental Setup for PIV Measurements

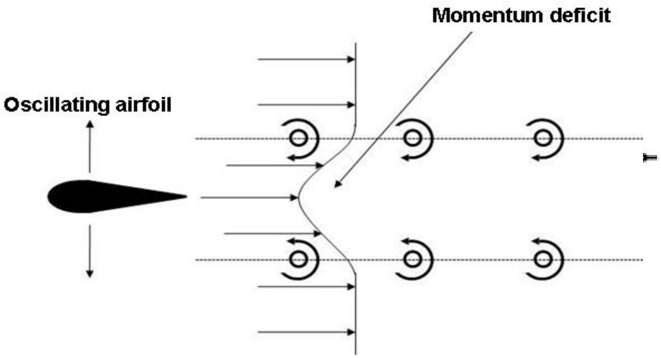


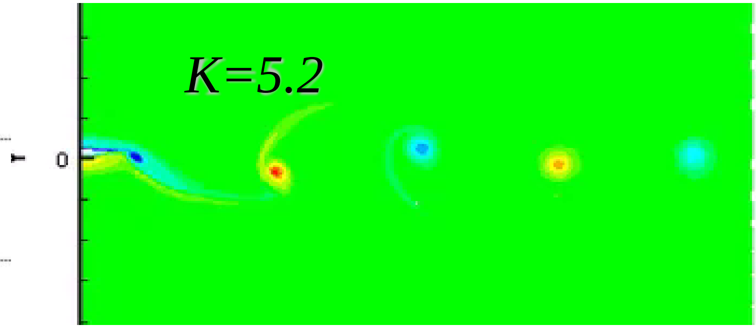


Test conditions:

- *Chord length:* *C=12.5mm*
- *Flapping frequency:* *f=60 Hz.*
- *Flapping amplitude:* *A/C = 0 ~2.0*
- *Incoming flow velocity:* *V=0.5 ~10 m/s*
- *Chord Reynolds No.:* *Re = 500 ~ 10,000*
- *Angle of Attack:* *AOA = 0, 10, 20 deg.*

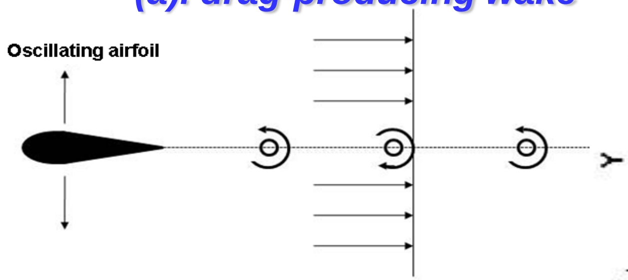
❑ Vortex Structures in the Wakes of 2-D Oscillating Airfoils

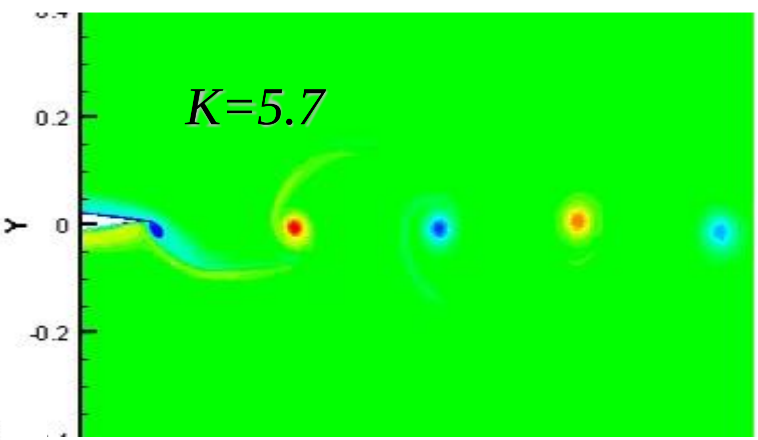




(a). drag-producing wake

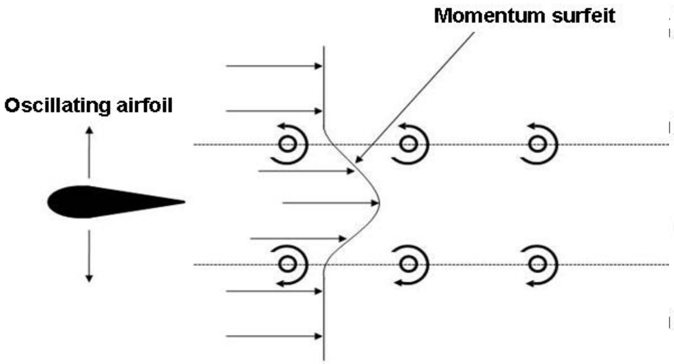
- von Karman Vortex Street or Drag Producing Wake causes momentum deficit

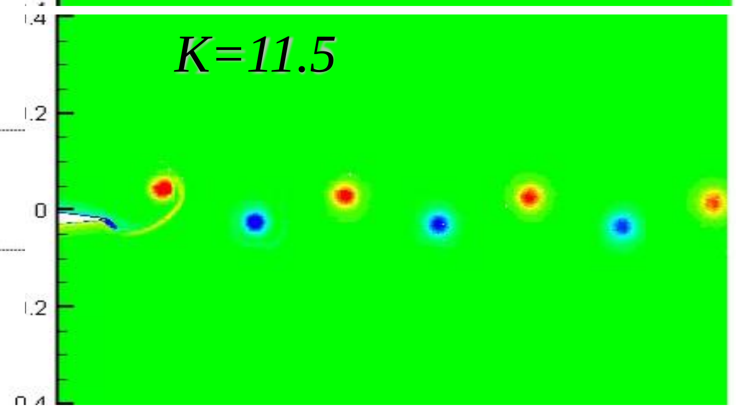




(b). Neutral wake

- Neutral Vortex



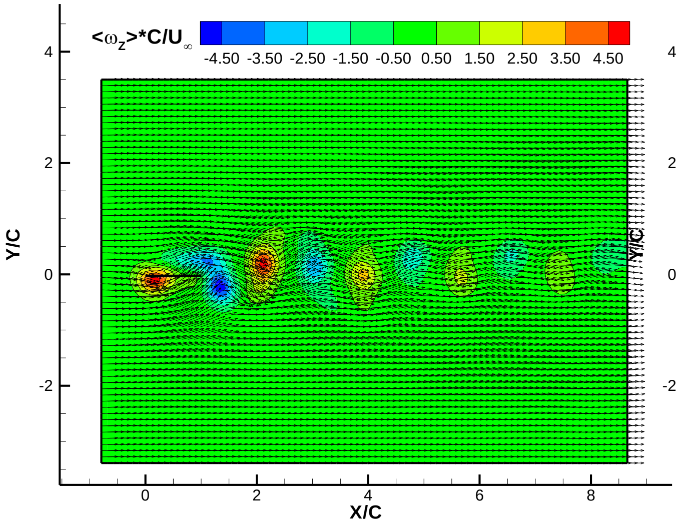


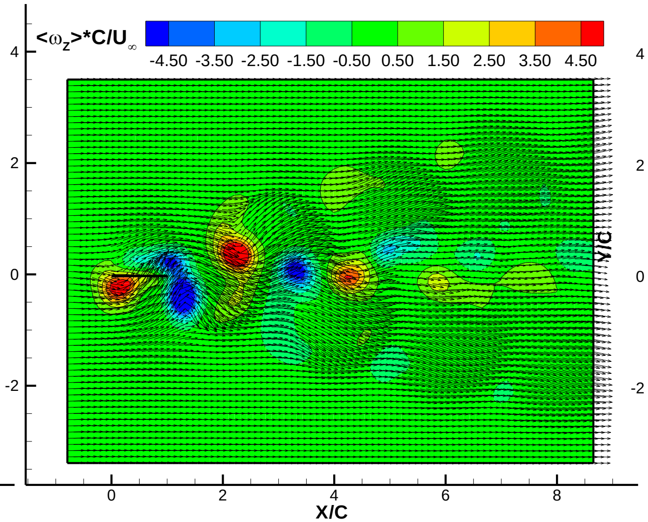
(c). Thrust producing wake

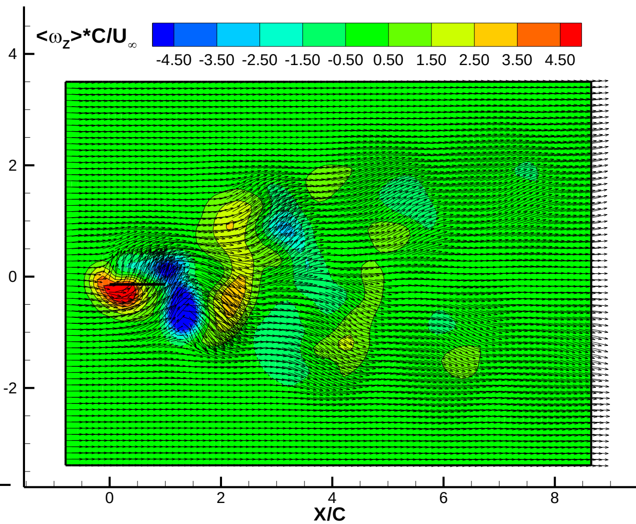
- Reverse von Karman Vortex Street or Thrust Producing Wake causes momentum surfeit

(Hu et al. 2011, EXIF)

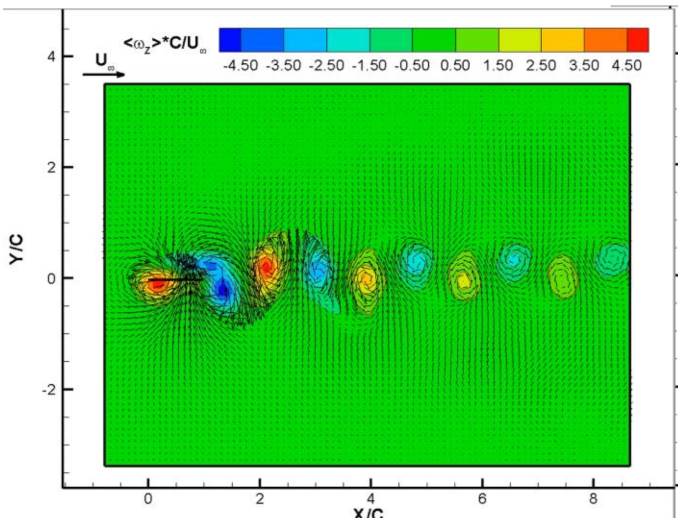
❑ Unsteady Flow Structures @ Different Wingspan Locations

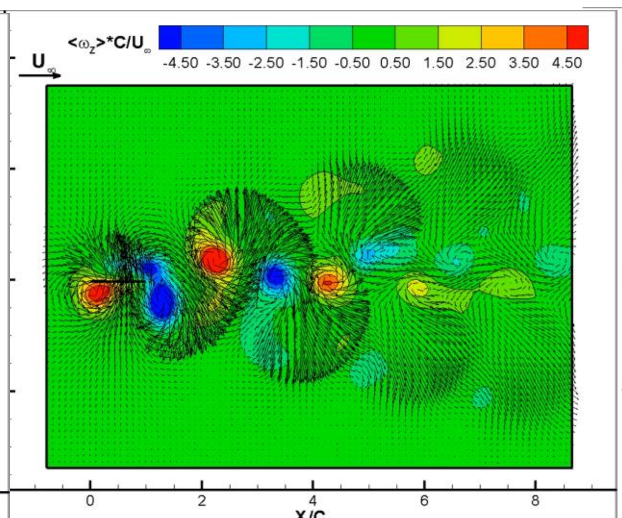


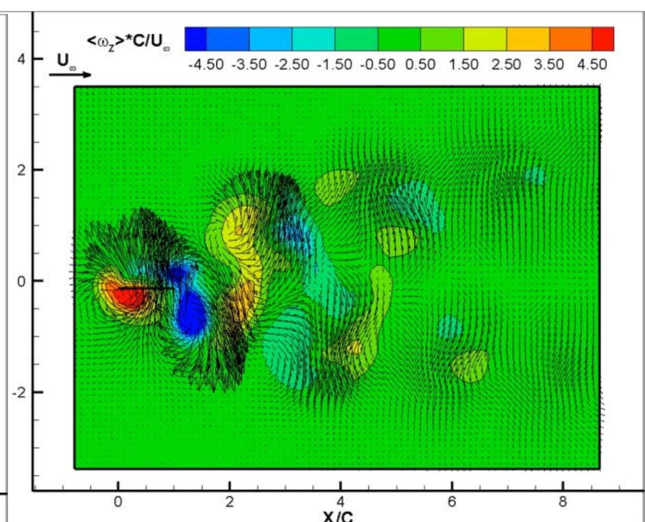




At 50% span location — *At 75% span location* — *At 100% span location (wingtip)*



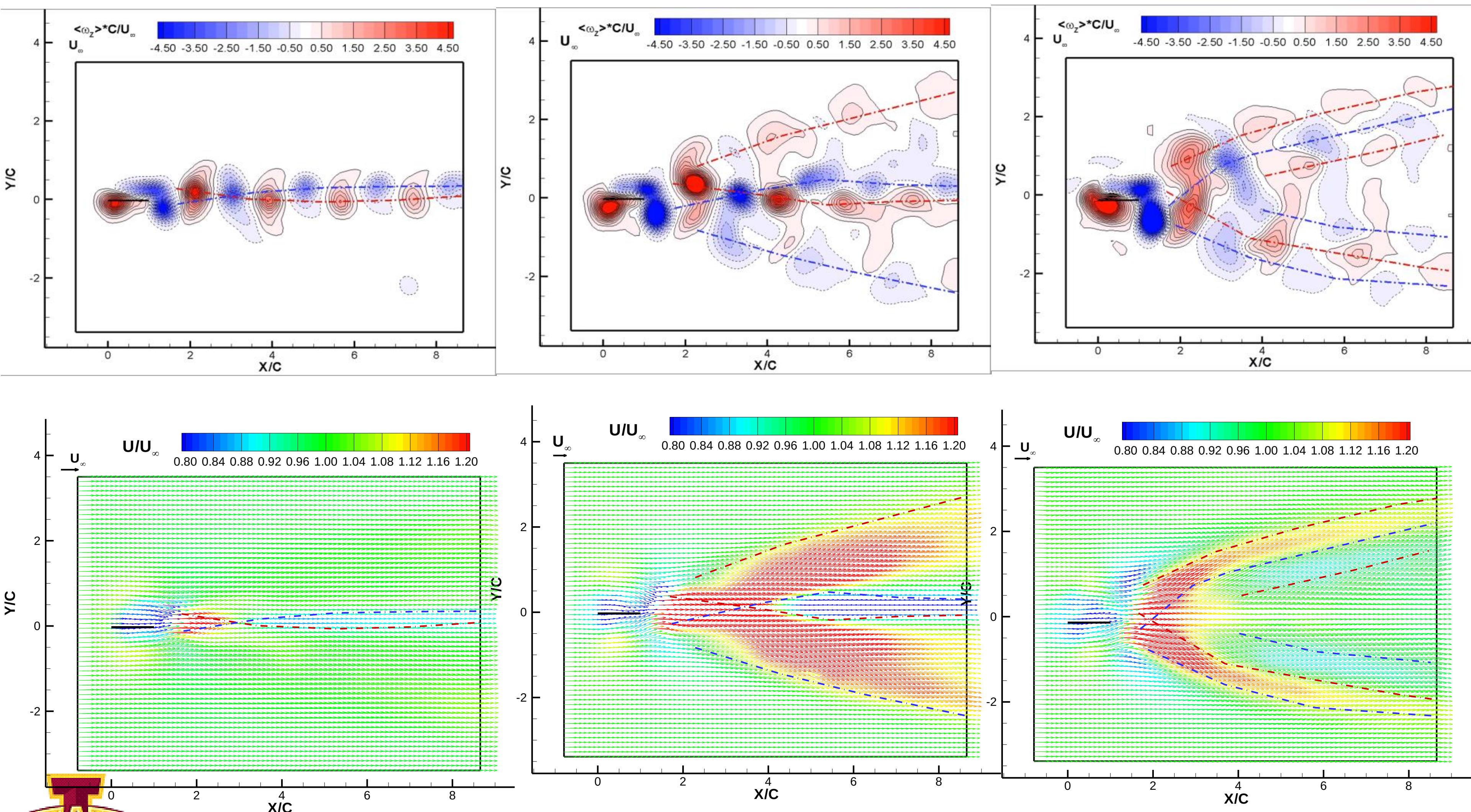




h = A/C = 1.3; k = 3.5, Str = 0.30, Re = 1,400, J = 0.69

Unsteady Flow Structures @ Different Wingspan Locations

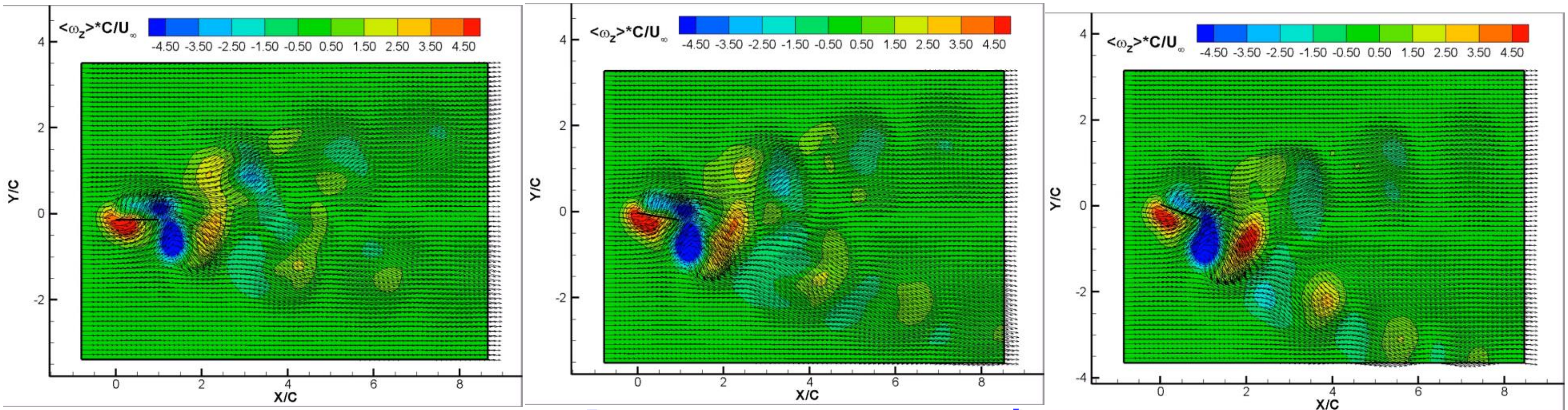
At 50% span location *At 75% span location* *At 100% span location (wingtip)*



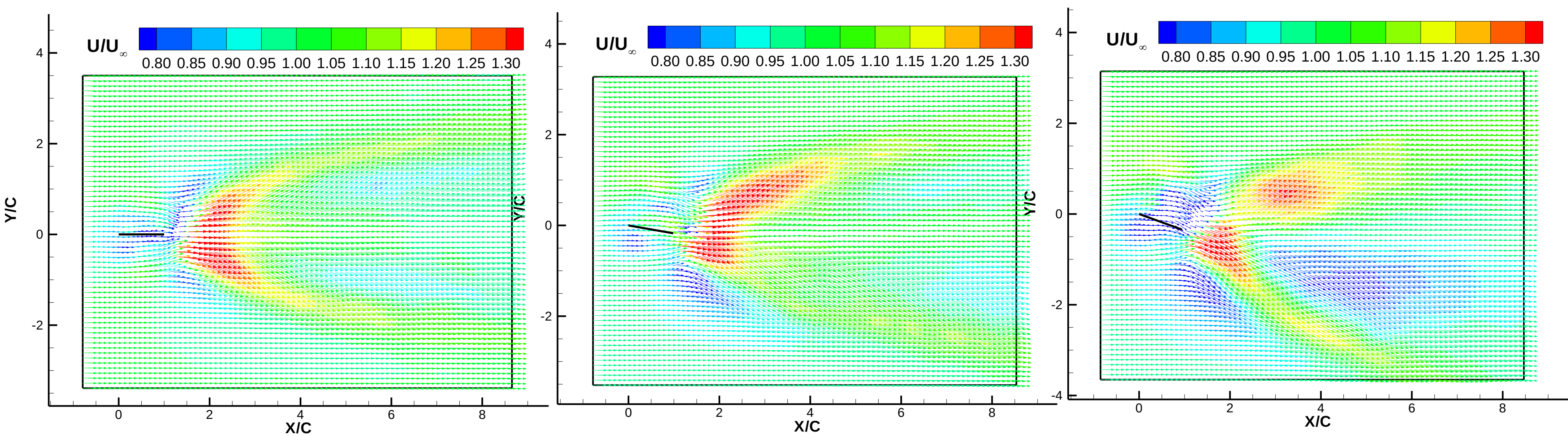
h = A/C = 1.3; k =3.5, Str = 0.30, Re=1,400, J = 0.69

Effects of Angle of Attack (measurements along wingtip Plane)

AOA = 0 deg. | AOA =10 deg. | AOA =20 deg.



Instantaneous measurement results



Ensemble-averaged measurement results

V=1.36 m/s, f=60Hz, A= 8.20 mm (h=0.65; k=3.52; J=0.69)

Dragonfly Flight with Tandem Wings

- *Four wings - tandem wing configurations*
- *The most agile and maneuverable insects .*
- *Top speed : 30km/h - 60km/h*
- *Wing beat frequency 27Hz - 170Hz*
- *Capable of hovering and flying backwards*
- *90º turns in under 3 wing beats*
- *Corrugated cross sectional wing profile - generates higher lift and delayed stall*

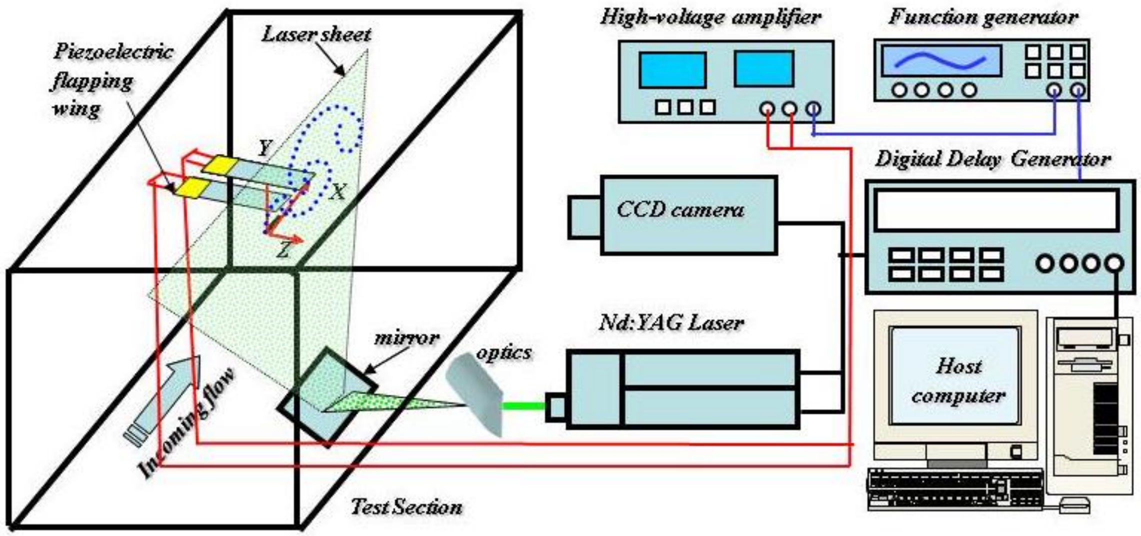
High Relative Phase Difference (Out-of-phase)

- *Relative phase difference between forewing and hind-wing is about 180º*
- *Basic flapping mode for dragonflies.*
- *Used during forward flight, takeoff and hovering.*
- *Better vibration suppression thereby allowing a stable posture during flight.*

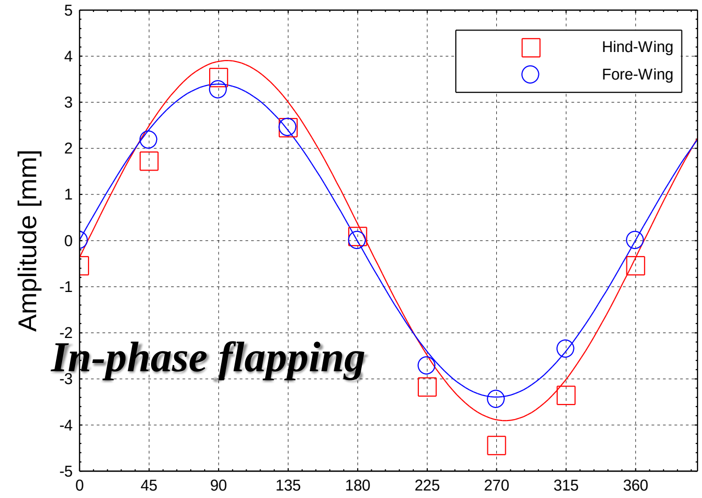
Low Relative Phase Difference (In-phase flapping)

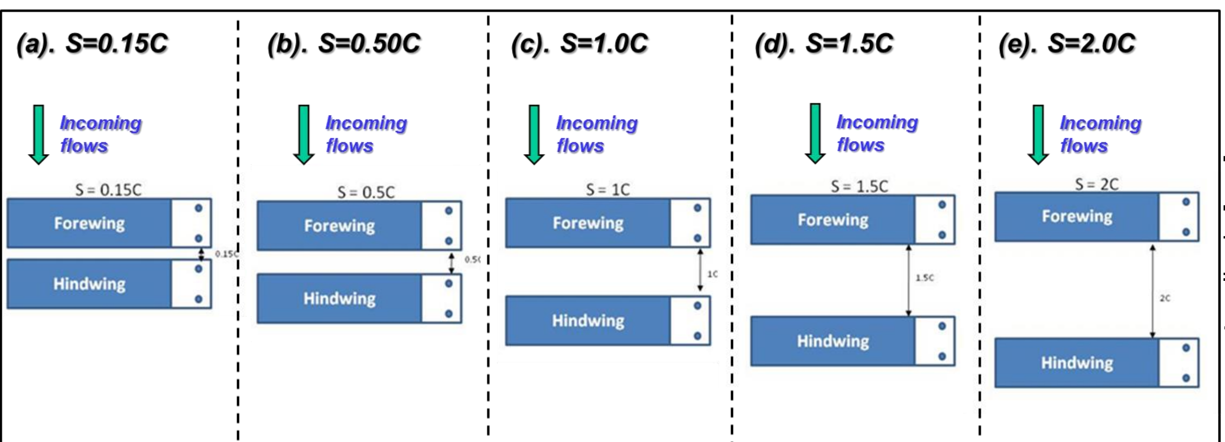
- *Relative phase difference between forewing and hind-wing close to 0º.*
- *Observed only in a few wing beats.*
- *Used during complex maneuvers, i.e., evading predators or intercepting prey.*
- *Results in higher energy consumption.*

Experimental Setup

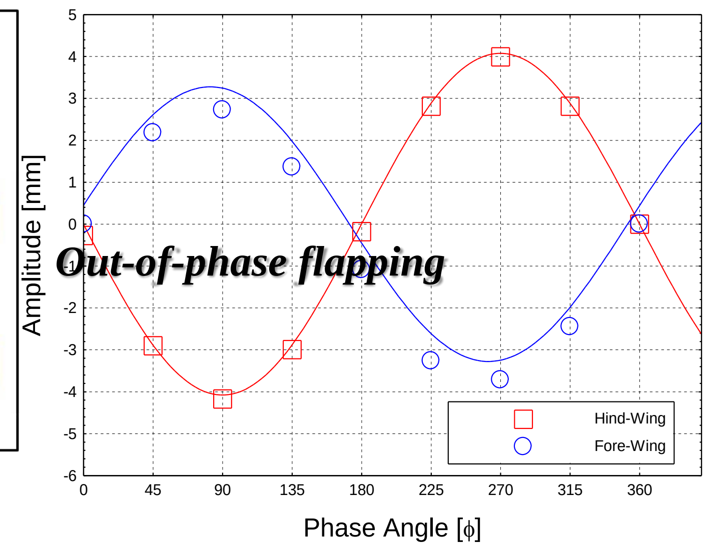


AoA = 0 ϕ = 0^o



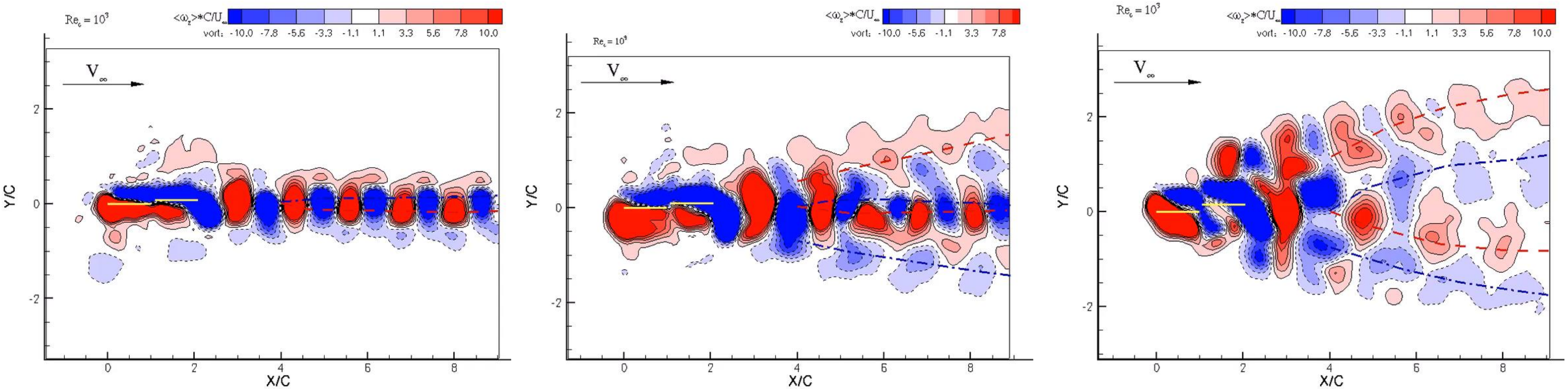


AoA = 0 ϕ = 180^o

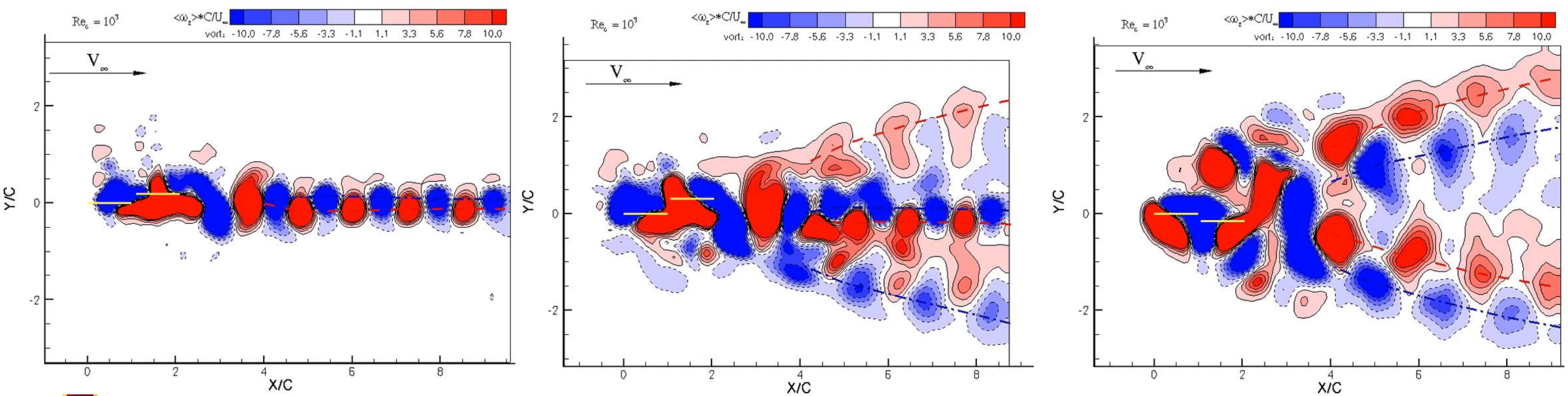


❑ Measurement Results of Flapping Wings with S=0.15C

50% Span *75% Span* *100% Span*



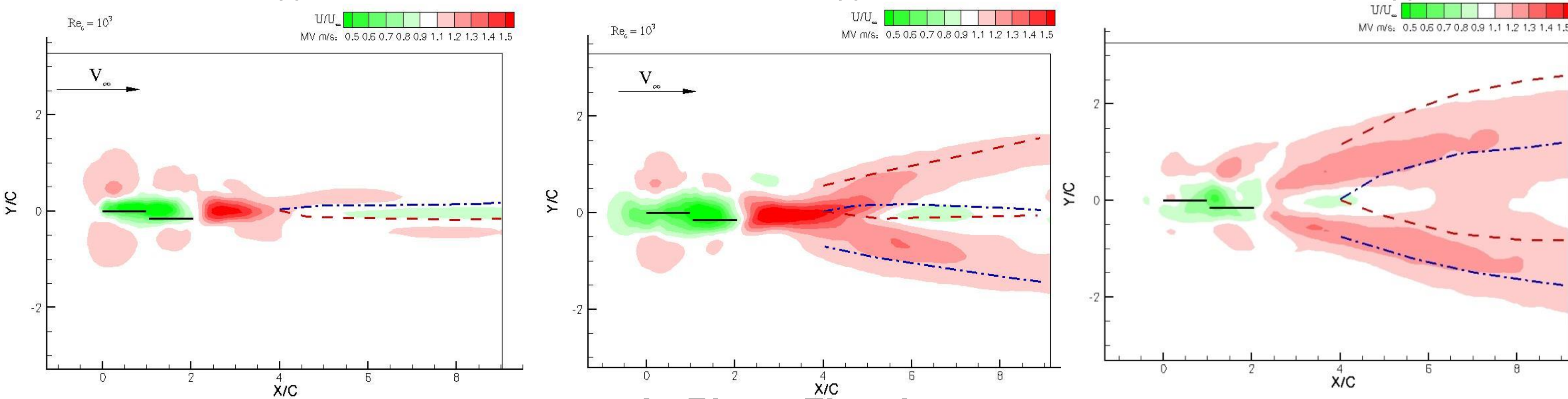
In-Phase Flapping



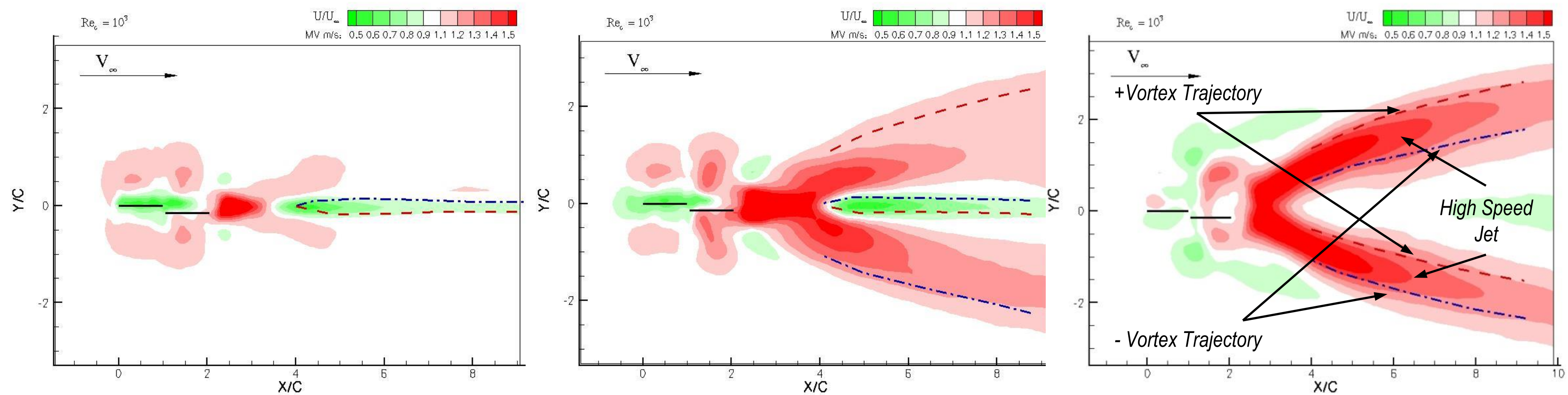
Out-of-Phase Flapping

❑ Time Averaged Measurement Results with S=0.15C

50% 75% 100%



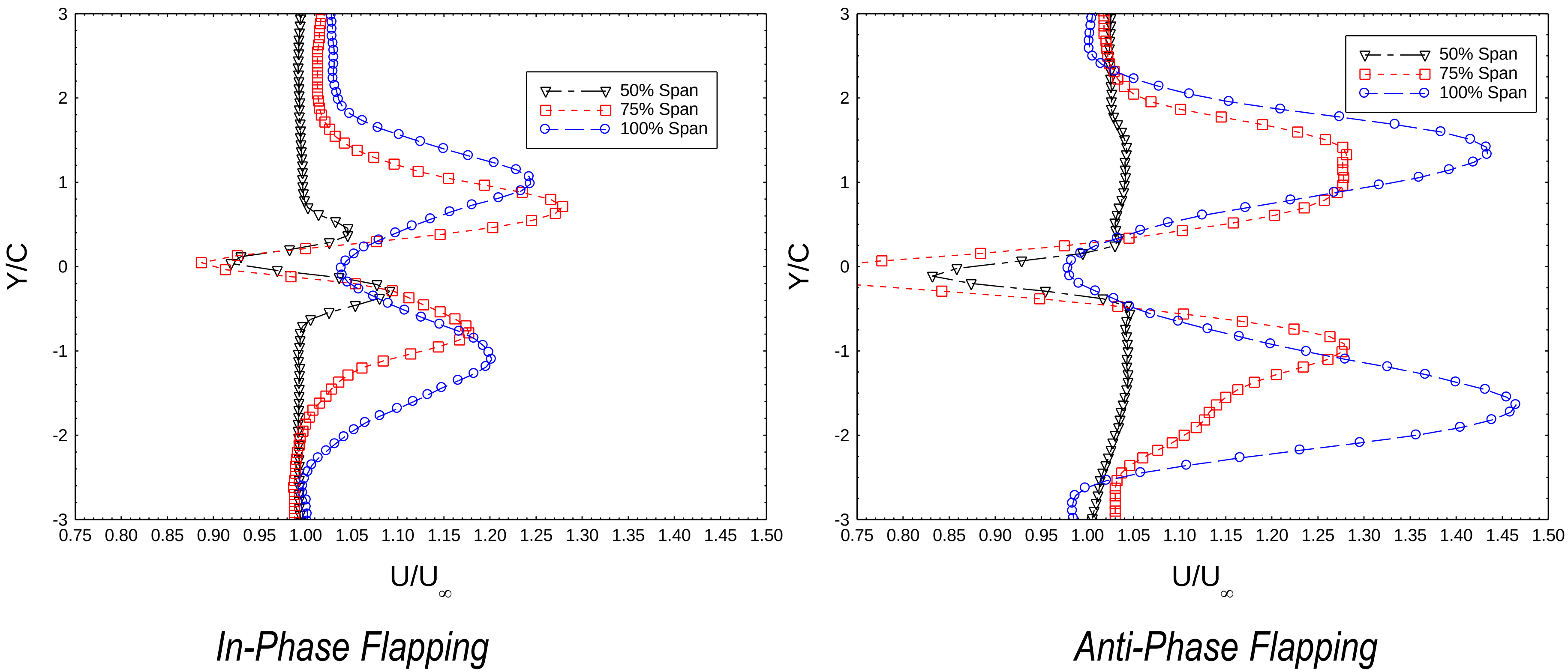
In-Phase Flapping



50% 75% 100%

Out-of-Phase Flapping

❑ Downstream Transverse Velocity Profiles with S= 0.15C

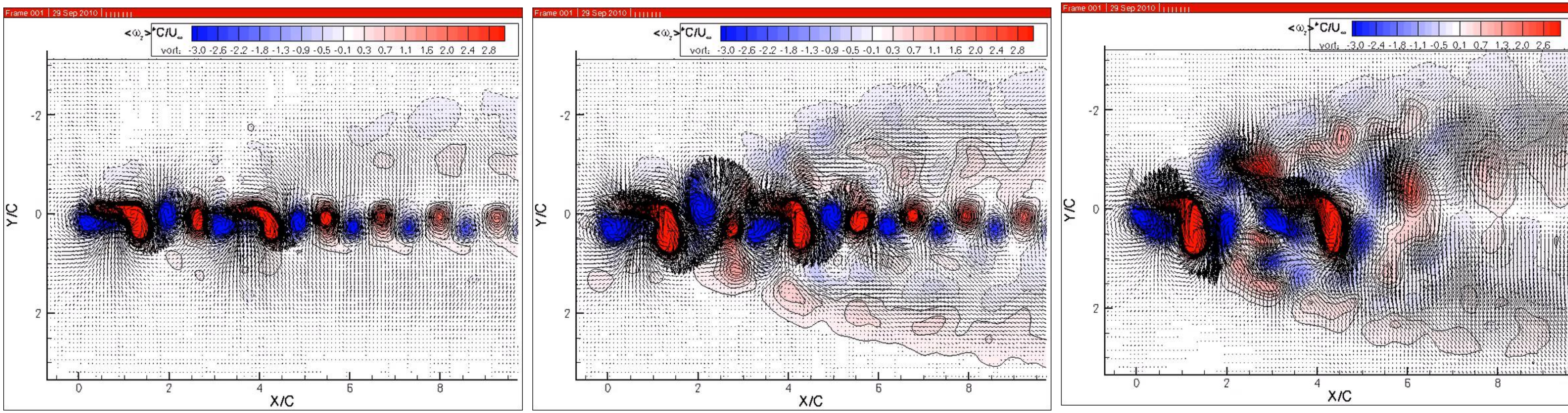


Time Averaged Wake Profile at X/C = 6

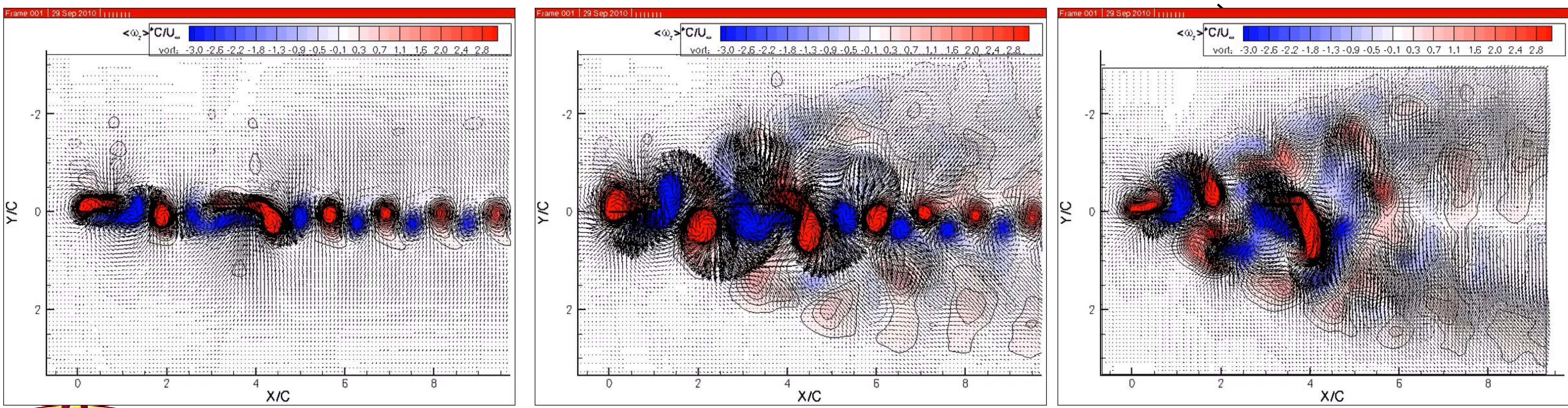
- ***Anti-phase flapping would generate more thrust in comparison with in-phase flapping.***

Measurement Results of In-Phase Flapping with S=2.0C

50% Span | 75% Span | 100% Span



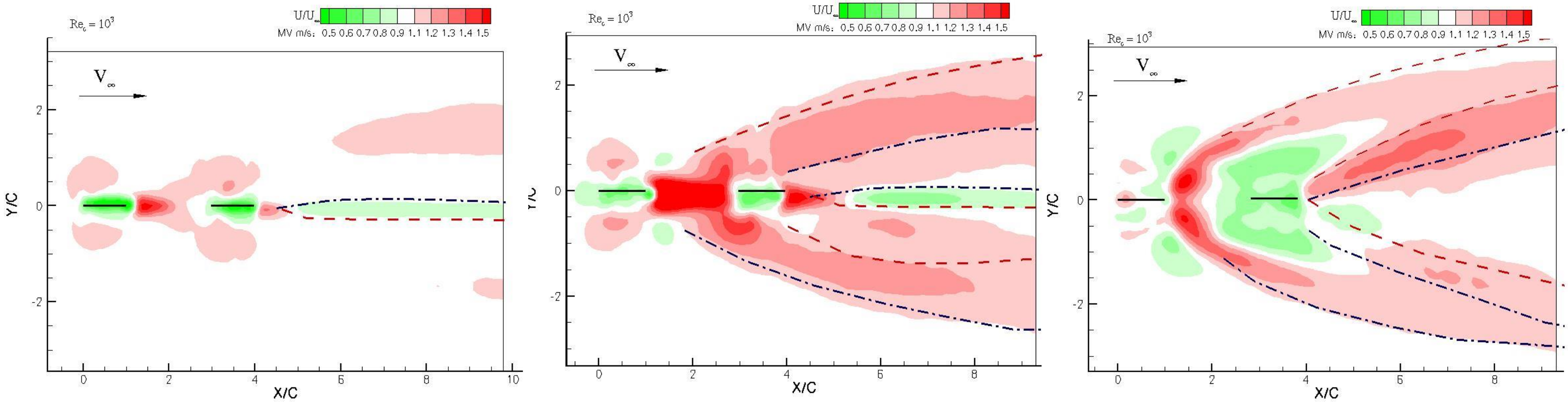
In-Phase Flapping



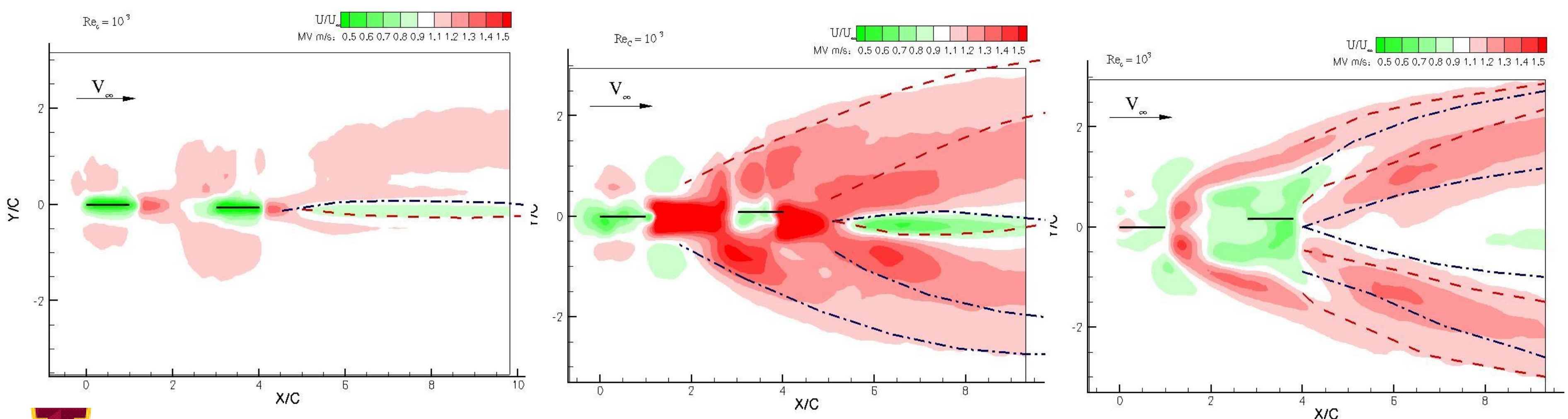
Out-of-Phase Flapping

Time Averaged Measurement Results with S = 2.0C

50% 75% 100%

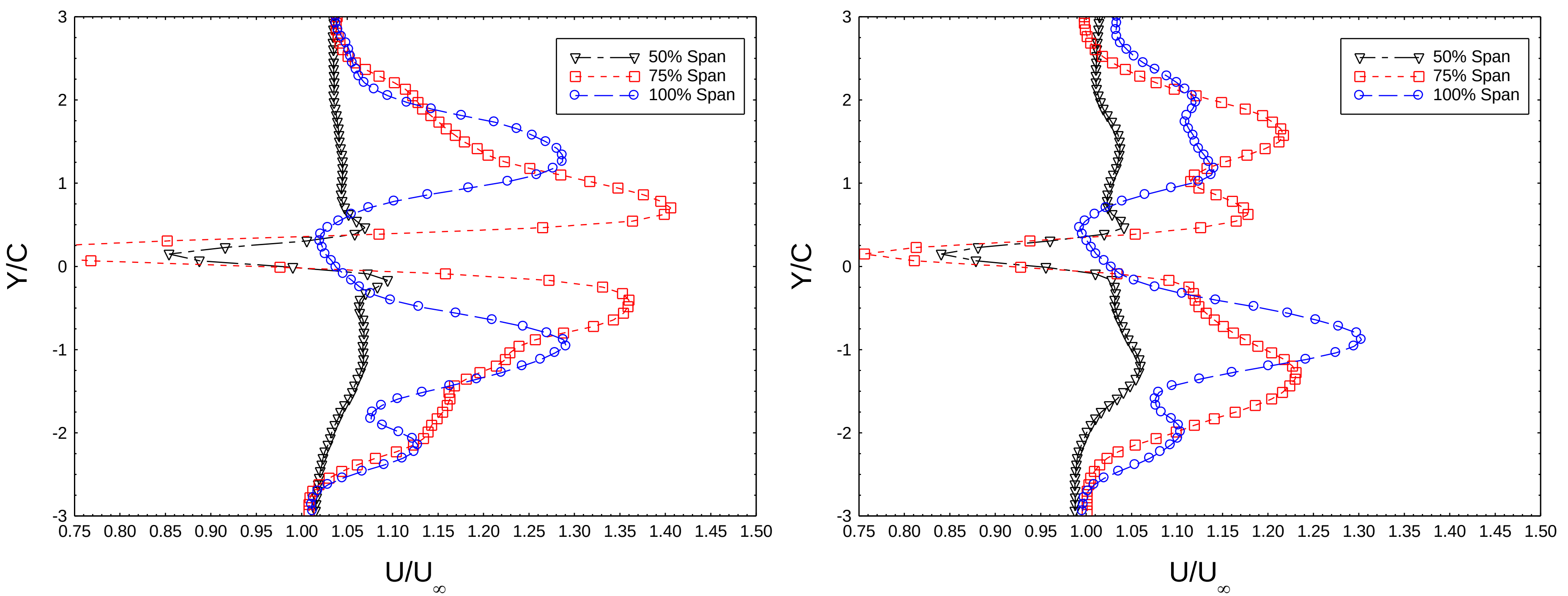


In-Phase Flapping



out-of-Phase Flapping

❑ Downstream Transverse Velocity Profiles with S= 2.0C



Anti-Phase Flapping *In-Phase Flapping*

Time Averaged Wake Profile at X/C = 6

- ***The difference in thrust generation between the anti-phase flapping and in-phase flapping would decrease as the spacing between the tandem wings increasing.***