





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

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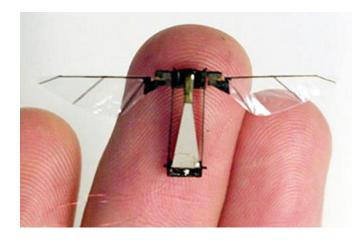
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□ UAV: Micro Air Vehicles (MAVs) and Nano Air Vehicle (NAV)



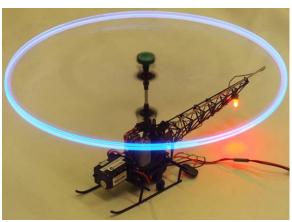
- MAVs: small air vehicles with wingspan less than 15 cm and capable of operating at speeds of about 10 m/s.
- NAVs: airborne vehicles no larger than 7.5 cm in length, width or height, capable of performing a useful military mission at an affordable cost and gross takeoff weight (GTOW) of less than or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



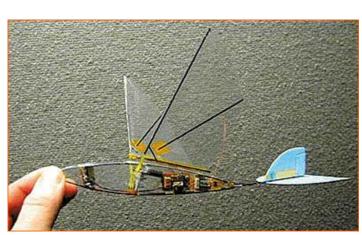
A flying robot developed by Harvard University



Fixed-Wing MAV design



Rotary-Wing MAV design



Flapping-Wing MAV design





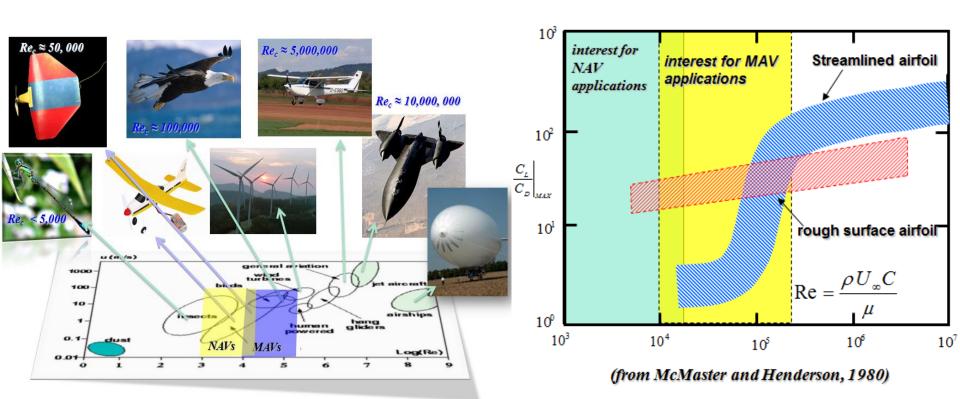




Aerodynamics of Micro-Air-Vehicles (MAVs)



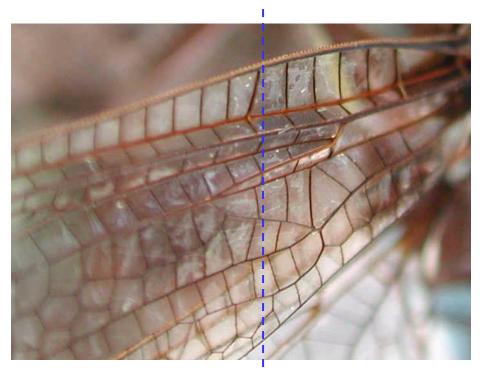
- "Scale-down" of conventional airfoils could not provide sufficient aerodynamic performance for MAV applications.
- It is very necessary and important to establish novel airfoil shape and wing planform design paradigms for MAVs or NAVs in order to achieve superb aerodynamic performances to improve their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

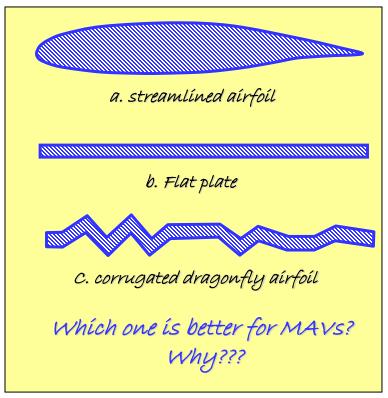




 $Re = \rho U L/\mu$

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



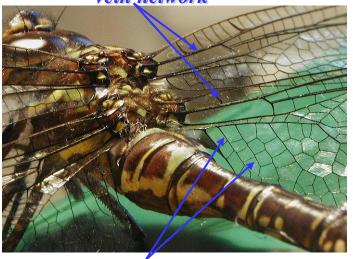




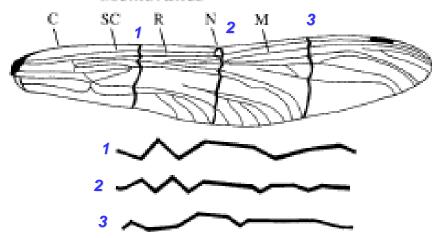
Bio-inspired Corrugated Airfoil for MAY Applications



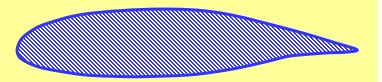
Vein network



Membranes



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



a. streamlined airfoil

b. Flat plate



C. corrugated dragonfly airfoil

Which one is better for MAVS? Why???

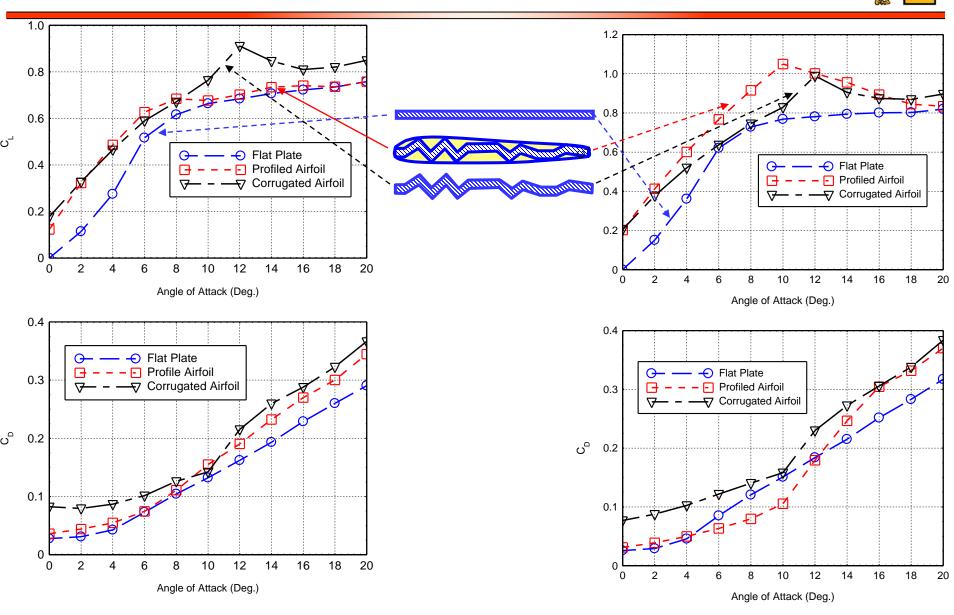


→ Aerodynamic Force Measurement Results

Re=50,000



Re=125,000

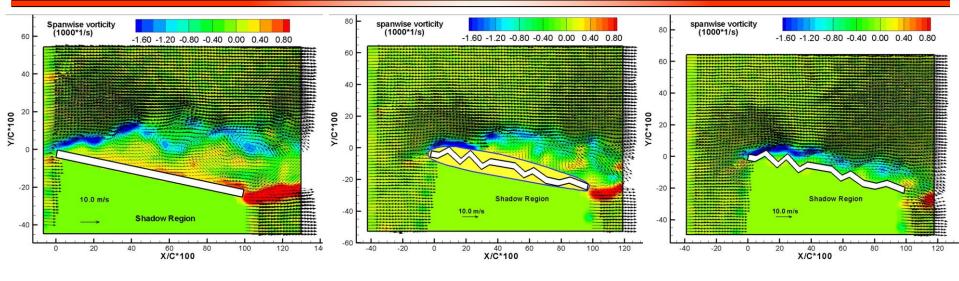


(Murphy and Hu, 2010, Experiments in Fluids)

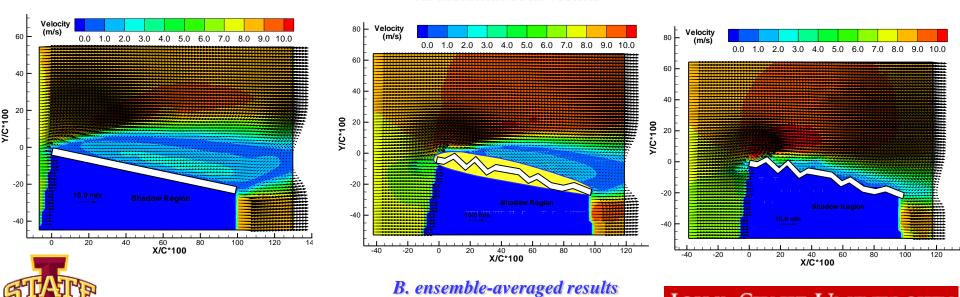
☐ PIV Measurement Results (AOA = 12.0 deg., Re=58,000)



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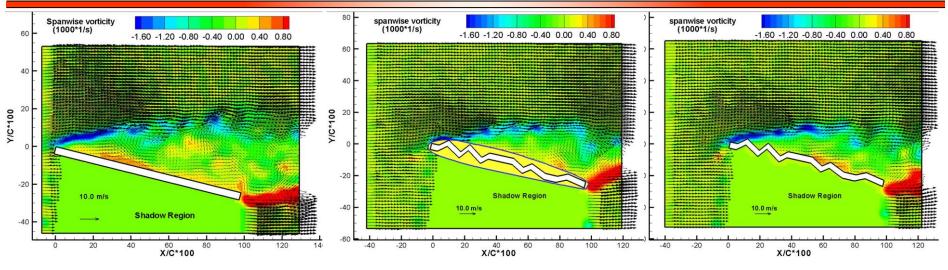


A. instantaneous results

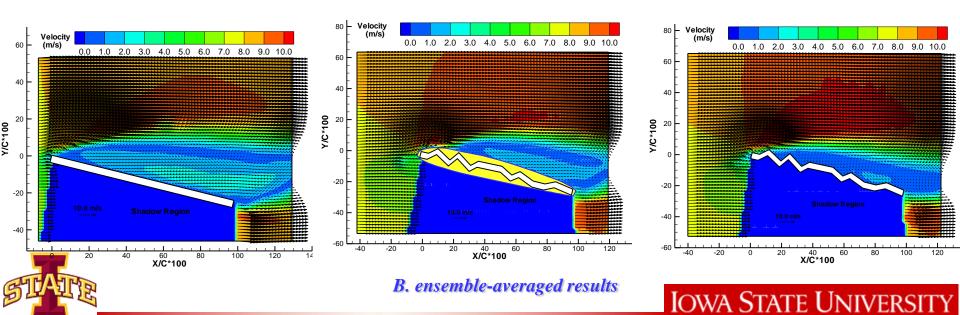


PIV Measurement Results (AOA = 14.0 deg., Re=58,000)



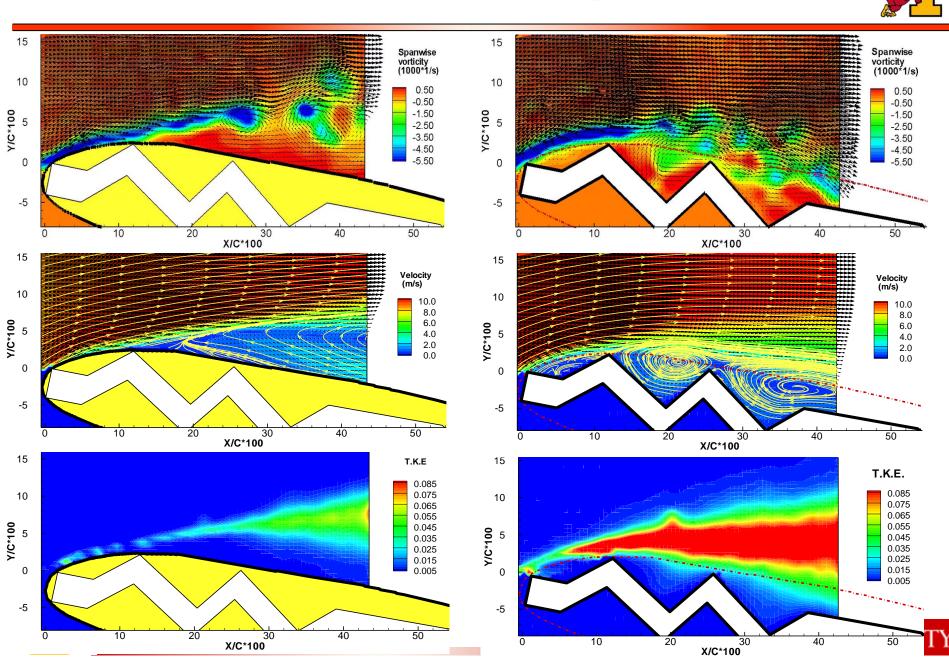


A. instantaneous results



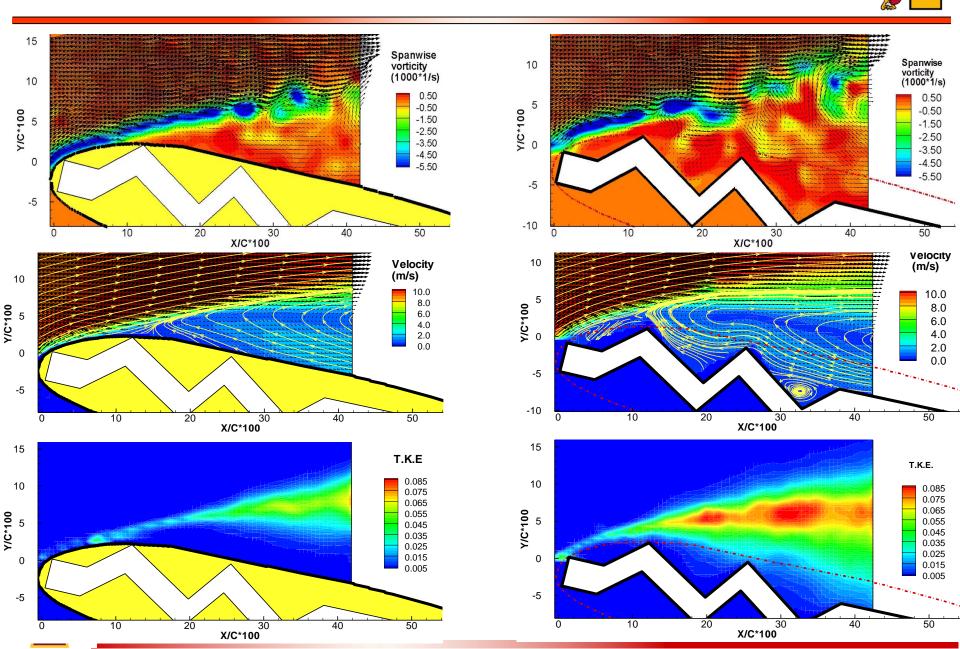
PIV Measurement Results (AOA = 12.0 deg., Re=58,000)



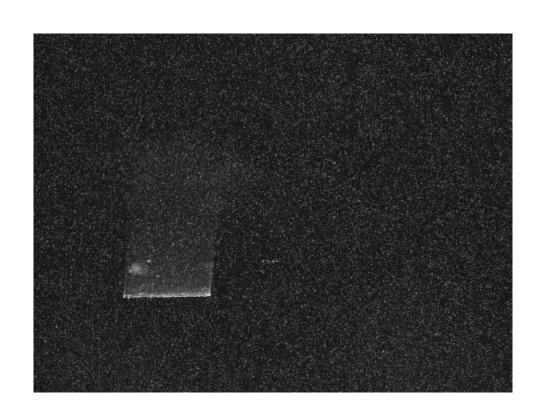


PIV Measurement Results (AOA = 14.0 deg., Re=58,000)





Topic #2: Unsteady Vortex Structures in the Wake of a Flapping Wing





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

- Co
- 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.



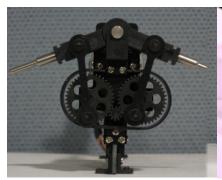






Flapping Mechanism for Flapping Wing MAVs and NAVs







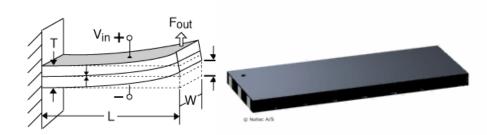
- Mechanical flapping mechanism
 - Bulky in size
 - Structure complex
 - Relatively low flapping frequency f < 15 Hz



Fruit fly @50 ~ 150Hz Dra

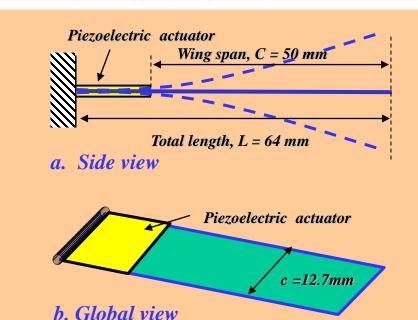


Dragonfly @ 30 ~ 100 Hz



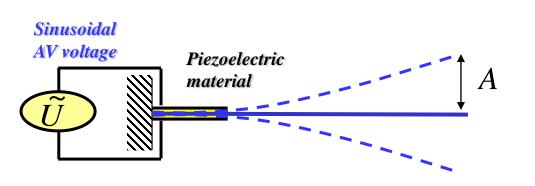
Piezoelectric actuator

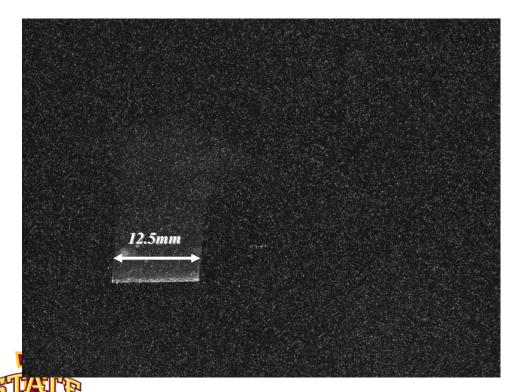
- Piezoelectric actuator-based flapping Mechanism
 - Compact in size
 - Simple structure
 - Much higher flapping frequency, f= 60~200Hz

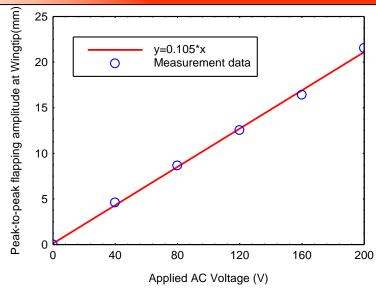


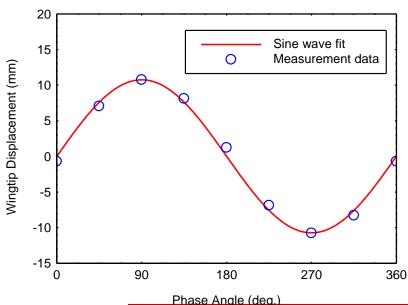
■ Dynamic Response of a Piezoelectric Flapping Wing









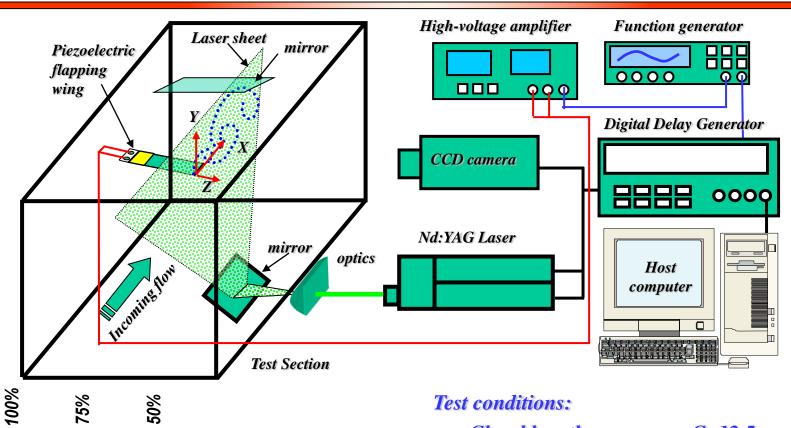


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Experimental Setup for PIV Measurements

Measurement Planes





Test conditions:

Chord length: C=12.5mm

Flapping frequency: f=60 Hz.

 $A/C = 0 \sim 2.0$ Flapping amplitude:

Incoming flow velocity: $V=0.5 \sim 10 \text{ m/s}$

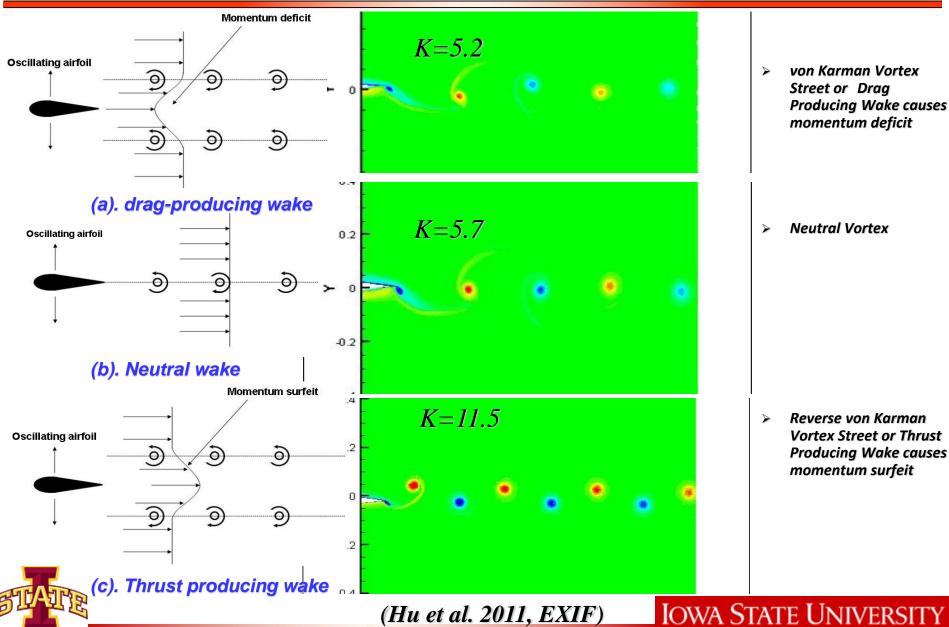
Chord Reynolds No.: $Re = 500 \sim 10,000$

Angle of Attack: AOA = 0, 10, 20 deg.

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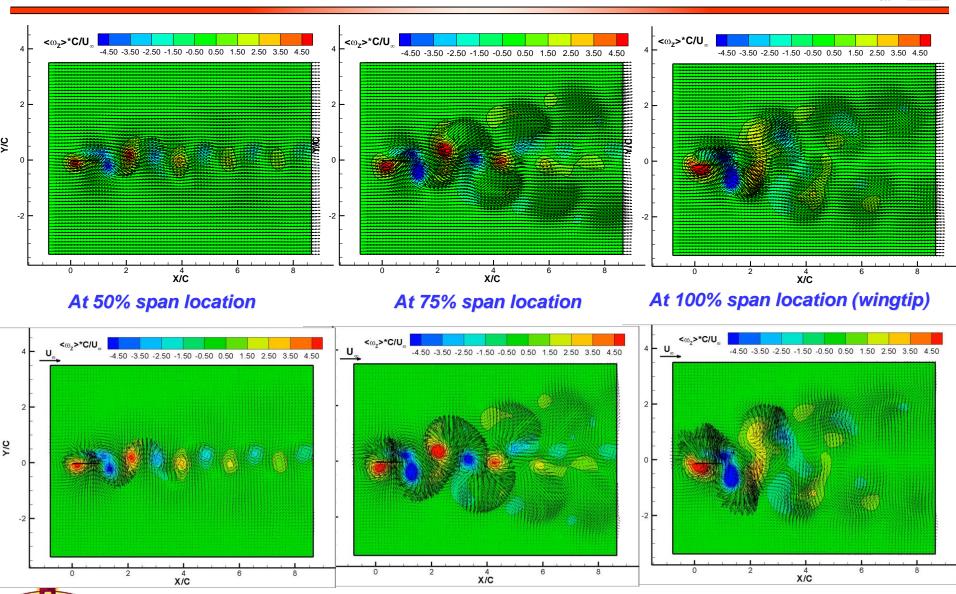
Vortex Structures in the Wakes of 2-D Oscillating Airfoils





Unsteady Flow Structures @ Different Wingspan Locations



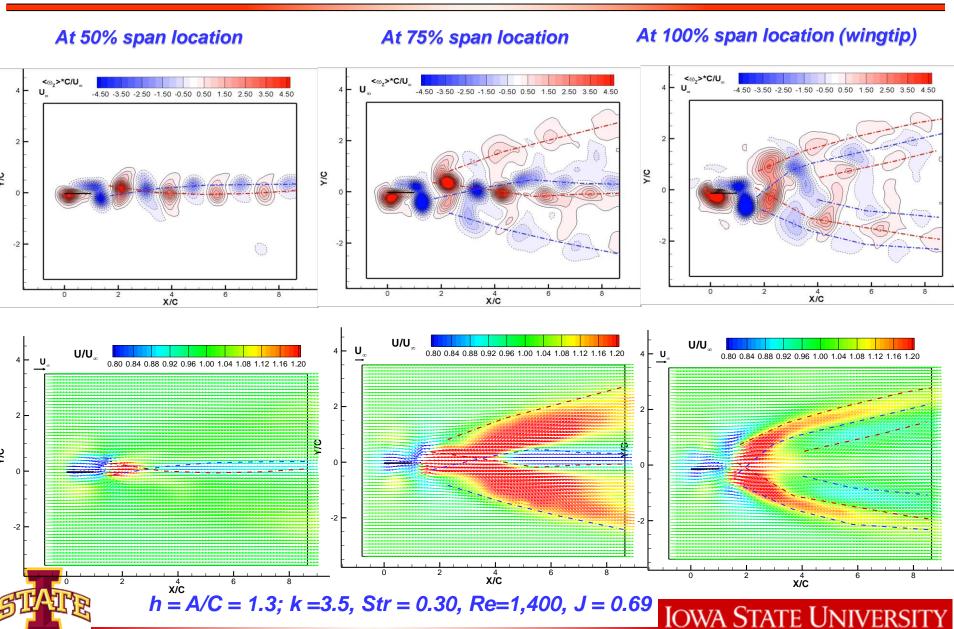


h = A/C = 1.3; k = 3.5, Str = 0.30, Re = 1,400, J = 0.69

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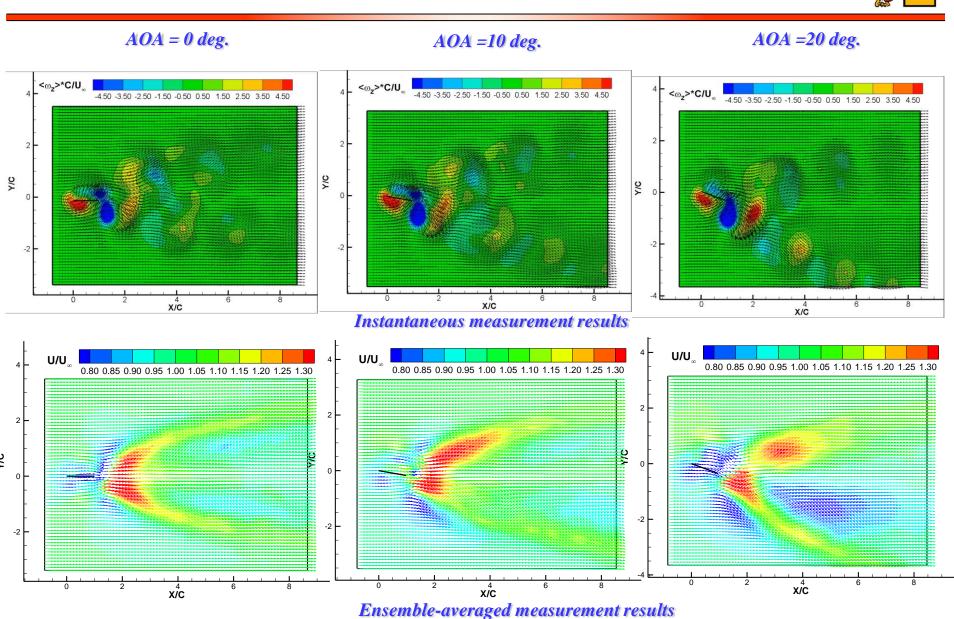
Unsteady Flow Structures @ Different Wingspan Locations





■ Effects of Angle of Attack (measurements along wingtip Plane)





Ensemble-averagea 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
- 90° 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 180°
- > 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)

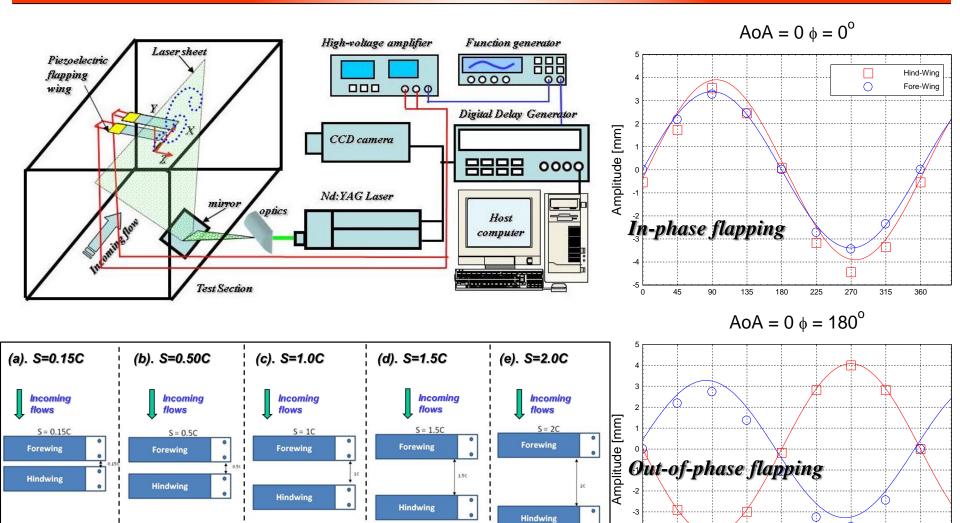
- > Relative phase difference between forewing and hind-wing close to 0°.
- > Observed only in a few wing beats.
- Used during complex maneuvers, i.e., evading predators or intercepting prey.
- Results in higher energy consumption.

Iowa State University

Experimental Setup



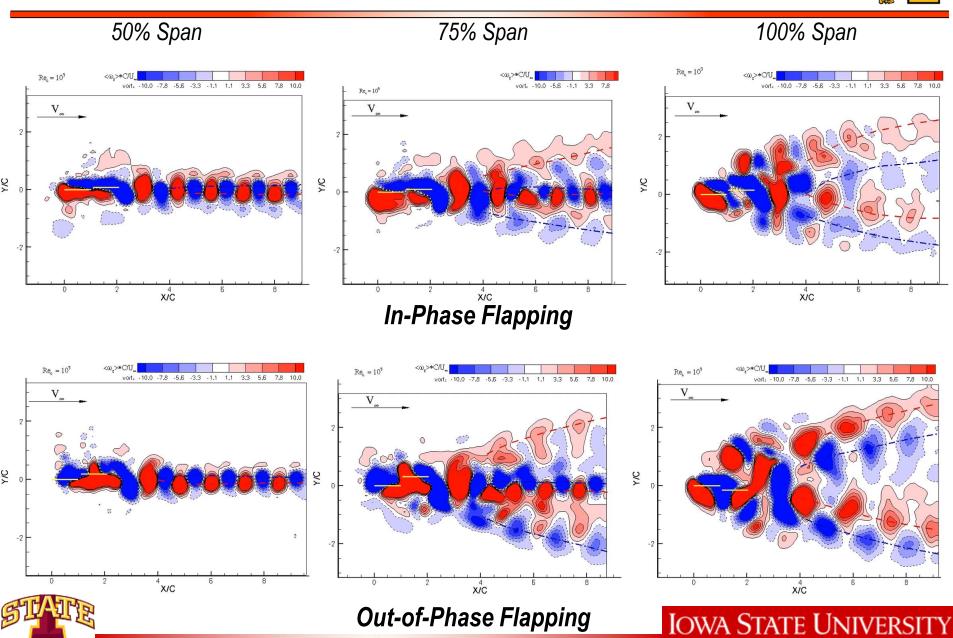
Hind-Wing Fore-Wing



45

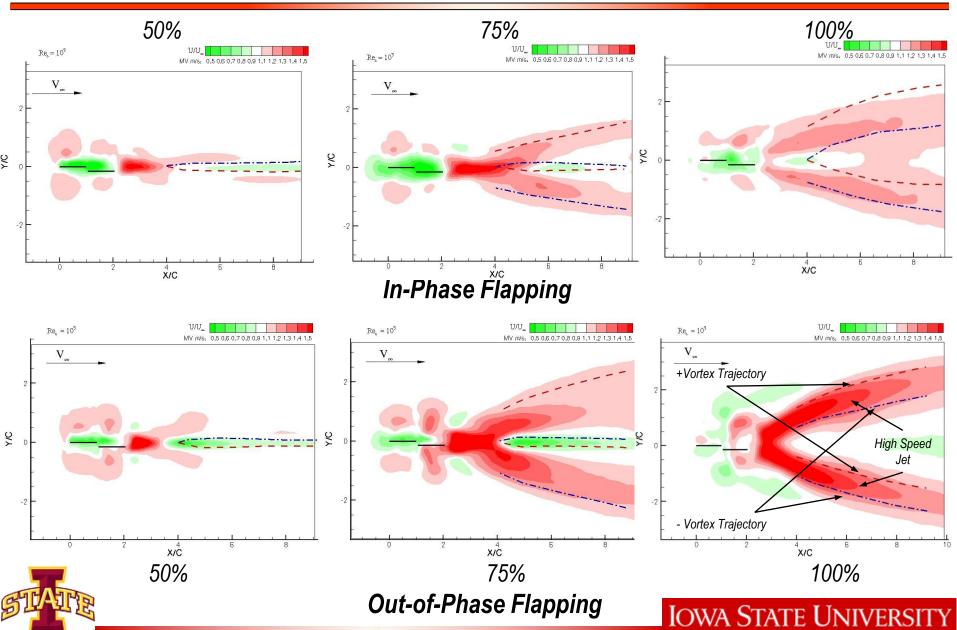
■ Measurement Results of Flapping Wings with S=0.15C value





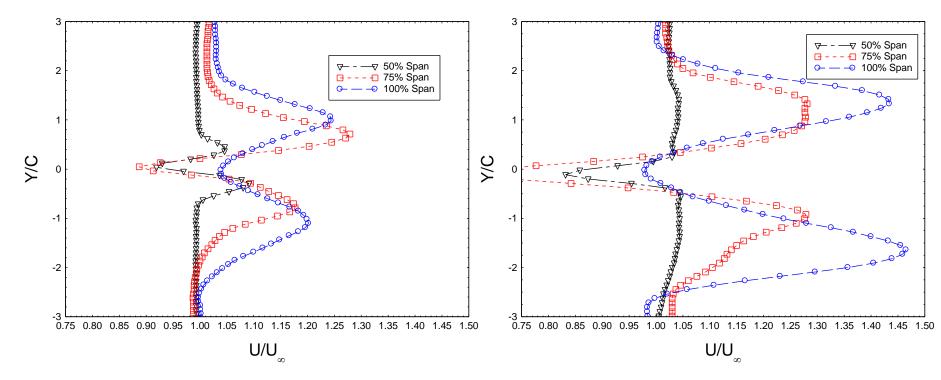
☐ Time Averaged Measurement Results with S=0.15C





Downstream Transverse Velocity Profiles with S= 0.15C





In-Phase Flapping

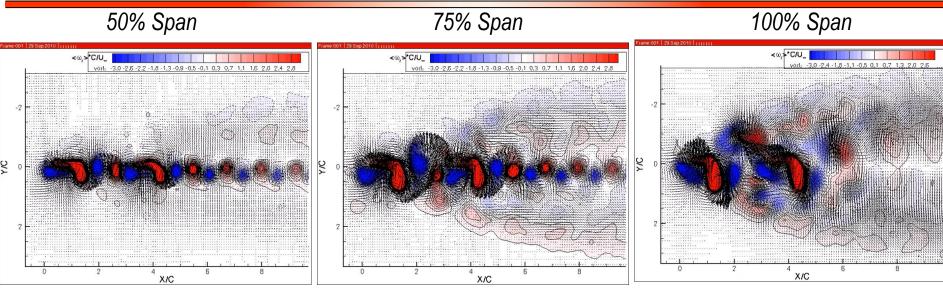
Anti-Phase Flapping

Time Averaged Wake Profile at X/C = 6

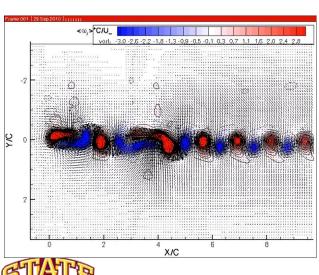
Anti-phase flapping would generate more thrust in comparison with in-phase flapping.

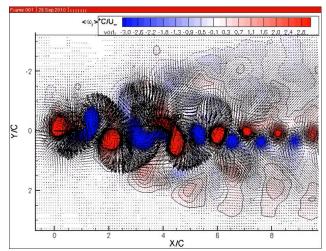


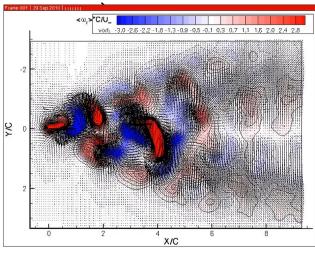
■ Measurement Results of In-Phase Flapping with S=2.00



In-Phase Flapping





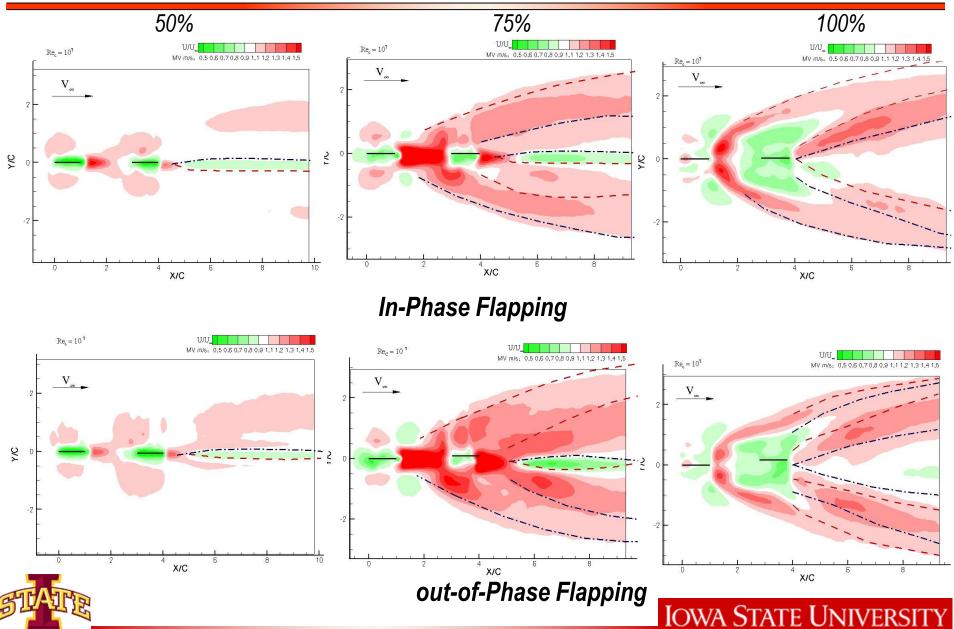


Out-of-Phase Flapping



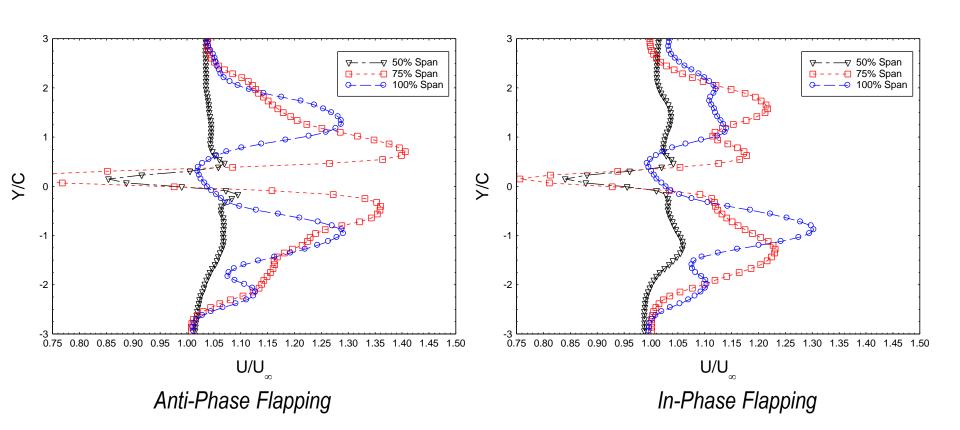
☐ Time Averaged Measurement Results with S = 2.0C





Downstream Transverse Velocity Profiles with S= 2.0C



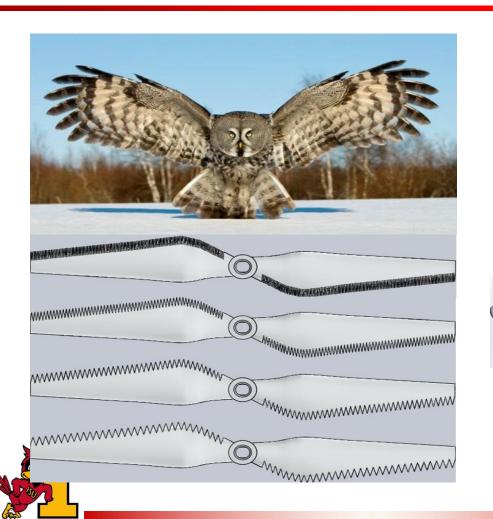


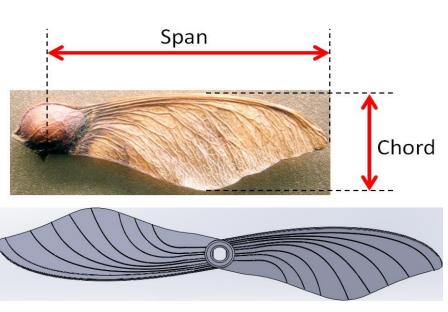
Time Averaged Wake Profile at X/C = 6

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



Quantifications of Aerodynamic and Aero-acoustic Performances of Bio-Inspired Propellers for UAY Applications





Introduction of Unmanned Aerial System (UAS)



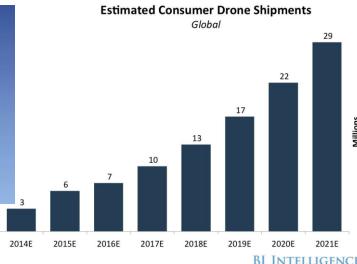
UAS is one of the most remarkable developments in aviation in recent years.



• MQ-9 (Prices: \$14.75 million)



DJI - Phantom 3 Quadcopter (price: ~\$500)



BI INTELLIGENCE BLINTERING NATION PROPERTY PROPE



Rescue operation

Video taking and mapping



Construction



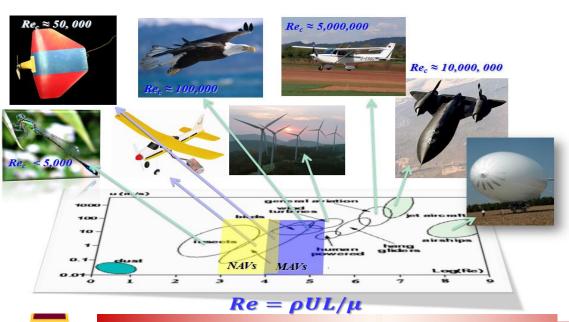
Propeller Design of UAS

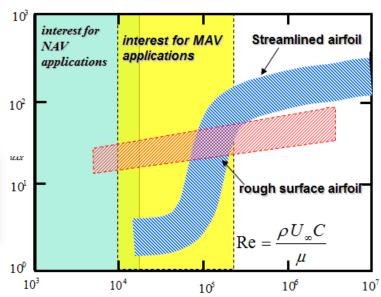






- "Scale-down" of conventional propellers may not provide optimized performance for UAS applications.
- It is very necessary and important to establish novel airfoil shape and wing planform design paradigms for MAVs or NAVs in order to achieve superb aerodynamic performances to improve their flight agility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





(from McMaster and Henderson, 1980)

□ Problems to Be Solved



Duration time



7 to 15 minutes~2200mah lion battery

Noise



Use of drones prohibited

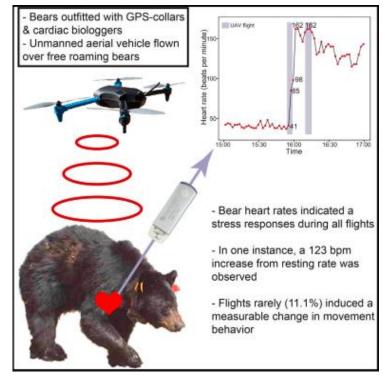
Motivation:

Can we solve these problems?

Ditmer et al. (2015)



15 to 25 minutes~5000mah lion battery

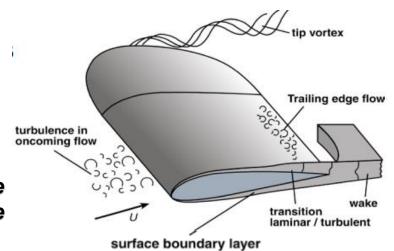


Bio-Inspiration for Noise Reduction



Aerodynamics Noise

- Inflow turbulence noise (less than 1k Hz)
- Airfoil self-noise
 - > Turbulent boundary layer trailing edge noise
 - Tip vortex formation noise
 - Separation/ stall noise
 - Trailing edge bluntness-vortex shedding noise
 - Laminar boundary layer vertex shedding noise



Oerlemans S. et. al (2012)

Owl Wing Inspiration

- Trailing edge fringe
- Leading edge comb
- Downy upper surface of the feather



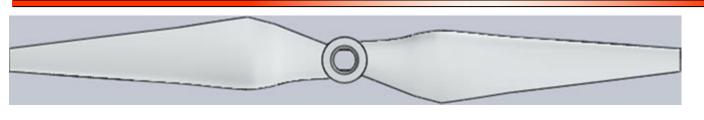
Saw-tooth serration











E63 airfoil

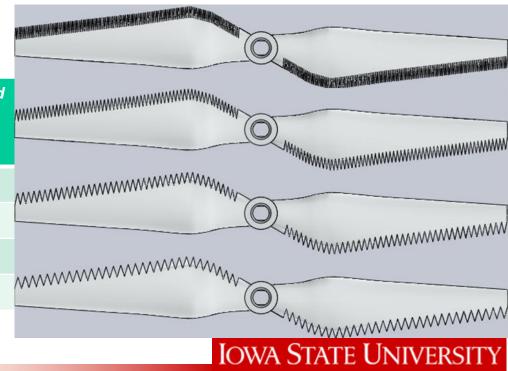
$$C_r = \frac{C_{tip}}{r}$$

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Design Parameters

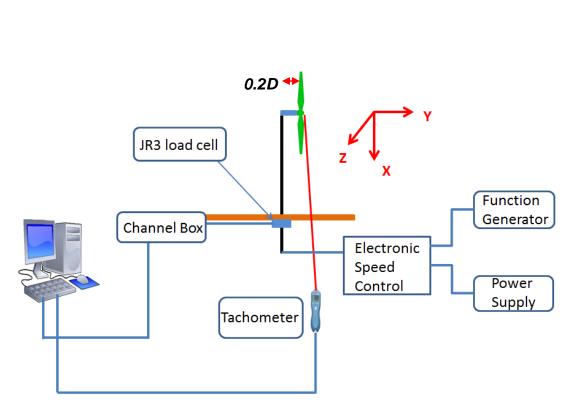
Design thrust	Radius	Tip chord	Root chord	Tip twist angle	Root twist angle
3N	120mm	8mm	30mm	11.6°	26.3°

	Serration height (2h)	Serrati on weight (λ)	Width/height ratio λ/h	inclined angle
SSTE(0.3)	6mm	0.9mm	0.3	8.5°
SSTE(0.3)	6mm	1.8mm	0.6	16.7°
SSTE(0.9)	6mm	2.7mm	0.9	24.2°
SSTE(1.2)	6mm	3.6mm	1.2	31°

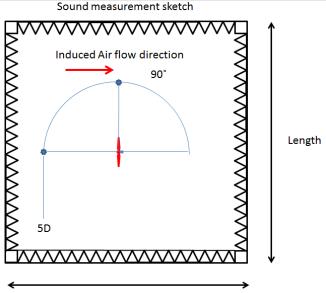


Quantification of Aerodynamic & Aeroacoustic Characteristics





High-sensitivity force-moment sensor (JR3 load cell)





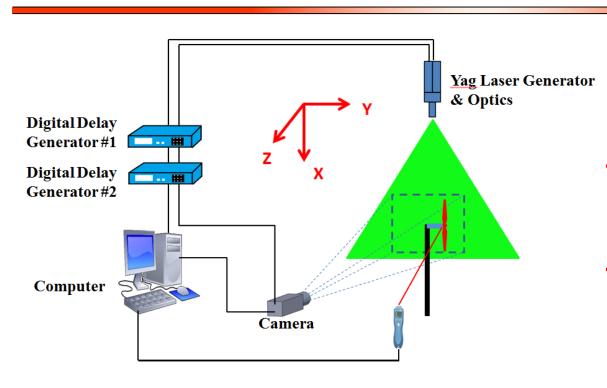
Width

Dimension: 12*12*9 feet



Experimental Setup for PIV Measurements





Size of particle:~1µm

Laser pulse power: 200mJ

Laser sheet thickness: 1mm

Laser wavelength: 532nm

High resolution CCD camera



Free run PIV



Aerodynamic Force Measurements



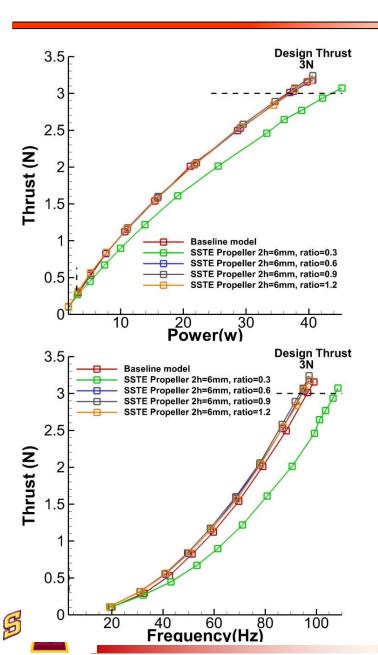
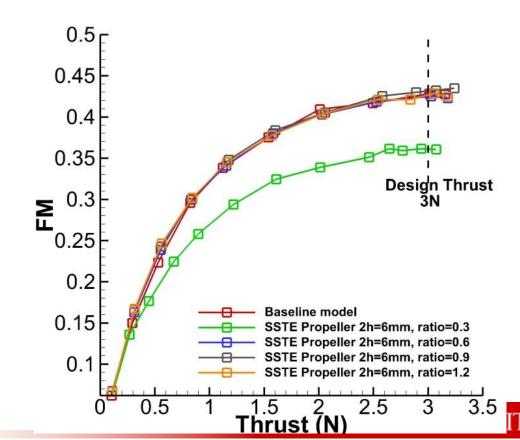
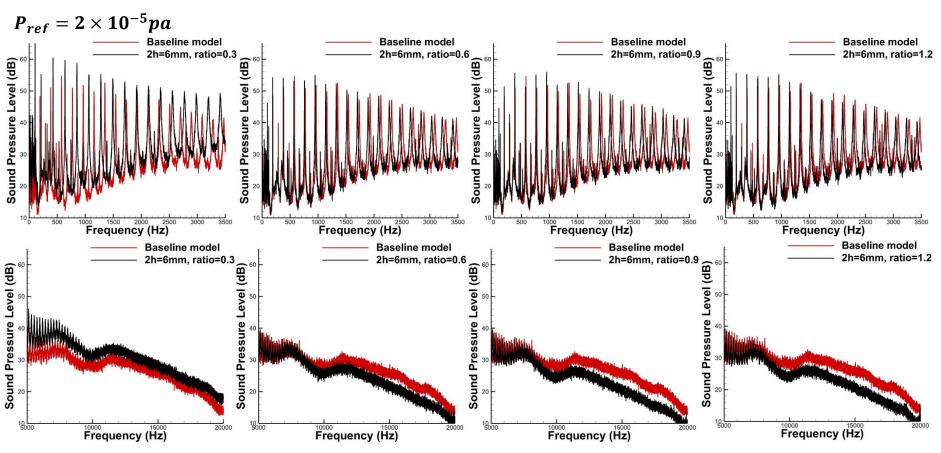


Figure of Merit $= \frac{Ideal \text{ power } required \text{ to hover}}{Actual \text{ power } required \text{ to hover}}$



■ Measurements of Aero-acoustic Performance





Increase noise 1.7dB

Reduce noise 0.9dB

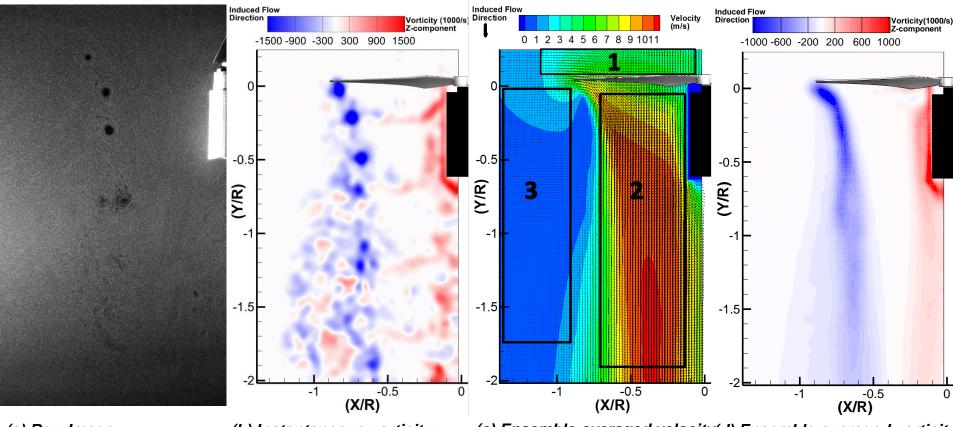
Reduce noise 1.4dB

Reduce noise 1.6dB



"Free-run" PIV Measurement Results





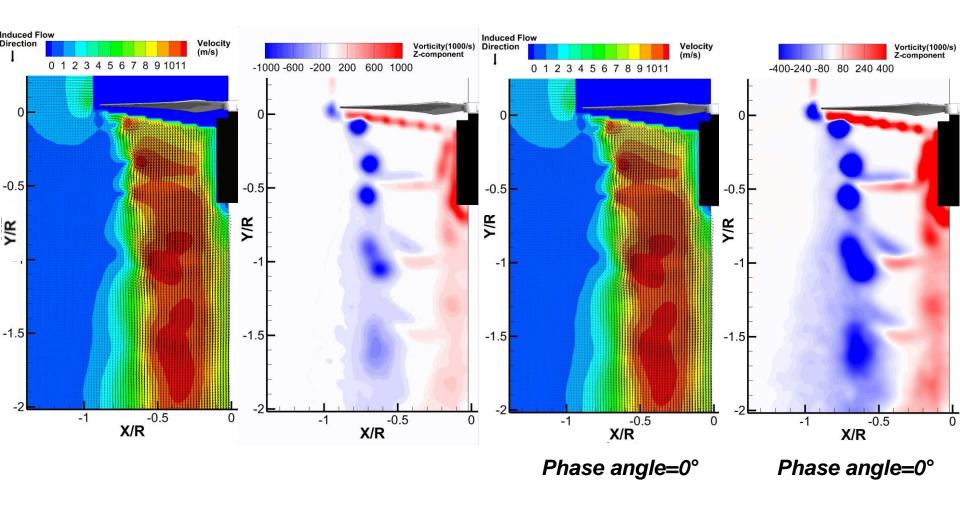
(a) Raw Image

- (b) Instantaneous vorticity
- (c) Ensemble-averaged velocity(d) Ensemble-averaged vorticity
 - . Inflow region
- 2. Induced flow region
- 3. Quiescent flow region



☐ "Phase-locked" PIV Measurement Results





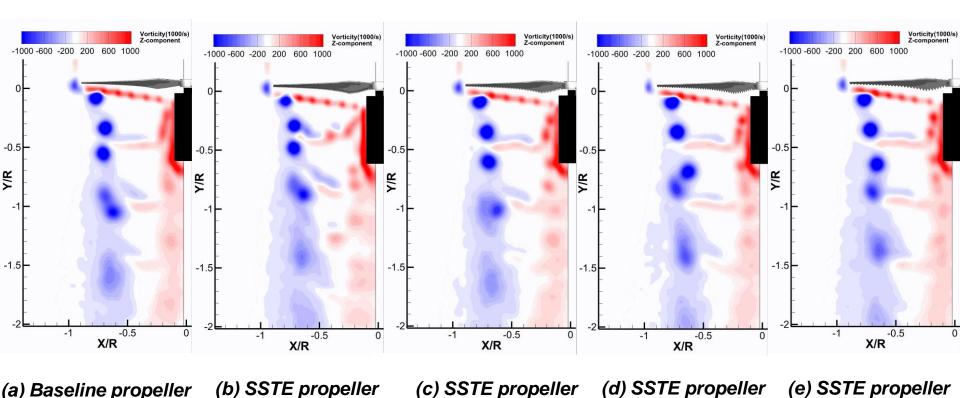


Comparison of Vorticity Distribution

(b) SSTE propeller

at $\lambda/h=0.3$





at $\lambda/h=0.6$



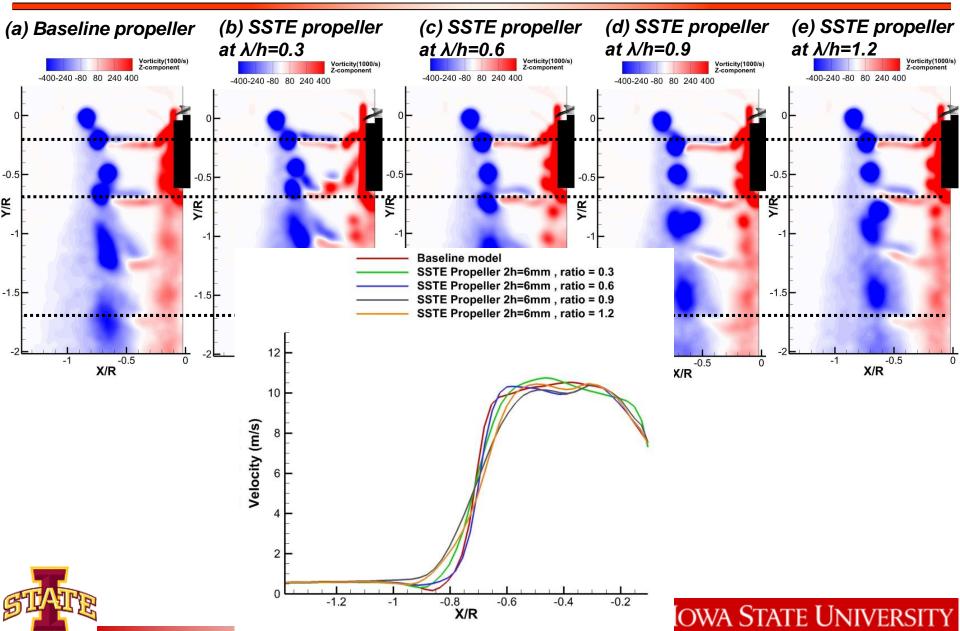
(a) Baseline propeller

at $\lambda/h=1.2$

at $\lambda/h=0.9$

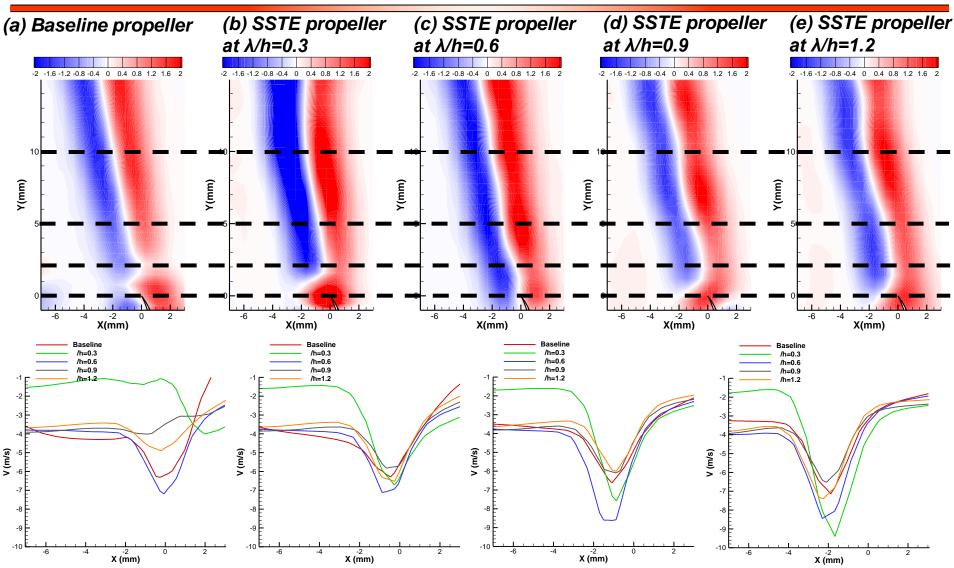
Comparison of Vorticity at the Phase Angle = 90°





Comparison of Vorticity Distribution at 75% Radius





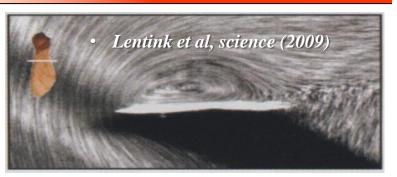
Velocity variation at different location at downstream of trailing edge

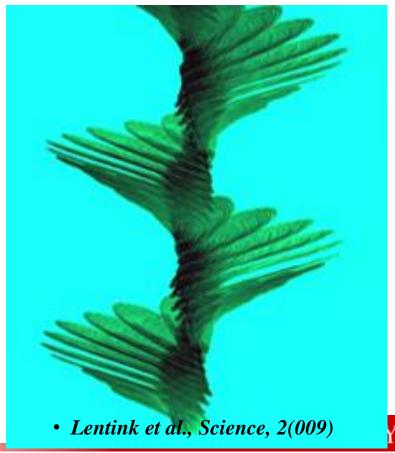
Flight Aerodynamics of Maple Seeds







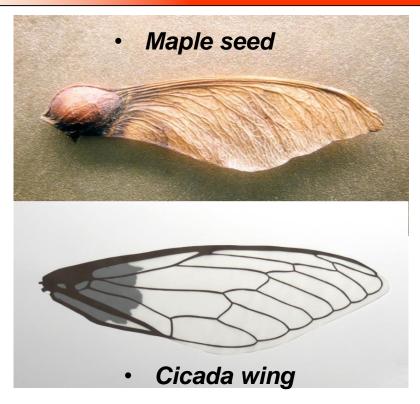


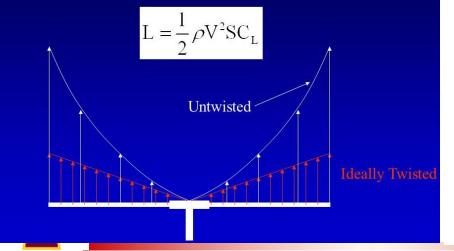


Bio-inspired Propeller Planform Design







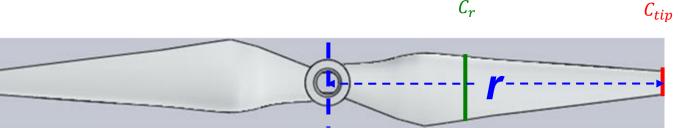


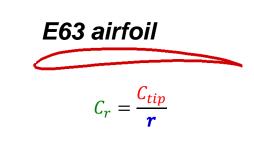
- Maple seed shape has a large area at high lift generated region, and chord Reynolds level in the region is also higher.
- With the increasing chord Reynolds number, the lift to drag ratio would increase significantly
- Small tip chord may benefit the tip vortex

Maple-Seed-Shaped Propeller (MSSP) Design



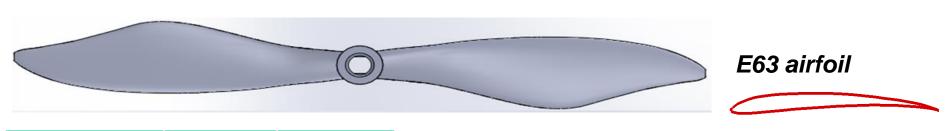






Design thrust	Radius	Tip chord	Root chord	Tip twist angle	Root twist angle
3N	120mm	11mm	34mm	11.6°	28.1°

Maple Seed Shaped Propeller (MSSP) Design Parameters



Design thrust	Radius	Tip chord	
3N	120mm	3.5mm	

Maximum chord	Tip twist angle	Root twist angle	
31mm	11.7°	18°	

The surface area and weight for the two propellers are kept as the same.

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□ Chord Reynolds Number and AOA Distribution

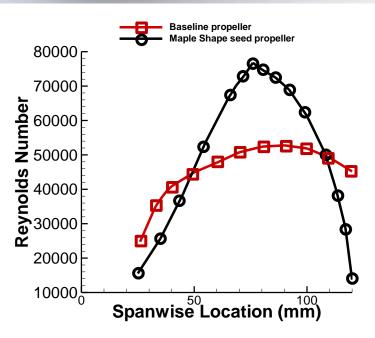


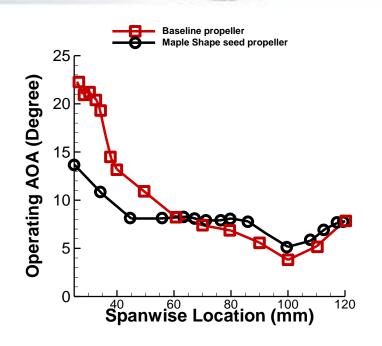
• Baseline Propeller









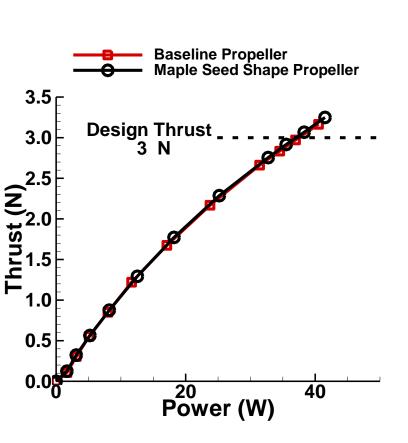


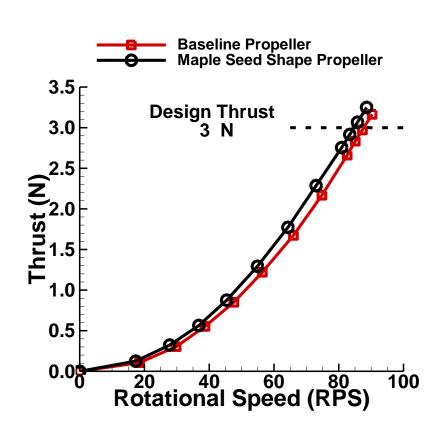
Re	40,000	50,000	60,000	70,000	80,000
Optimal AOA	6°	5°	4.75°	4.5°	4.25°



Aerodynamic Force Measurement Results



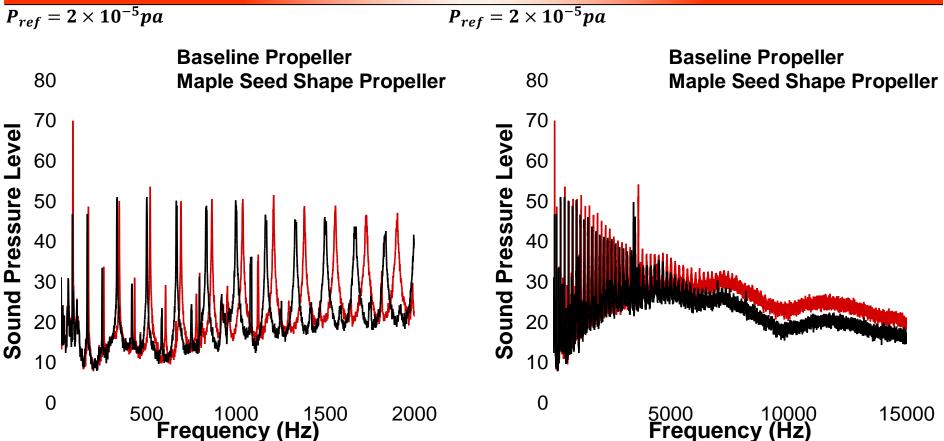




- MSSP would require the same amount of power in order to produce the designed thrust.
- MSSP can rotate slower, in comparison with the baseline case, to produce the same amount of thrust.

Sound Measurement Results

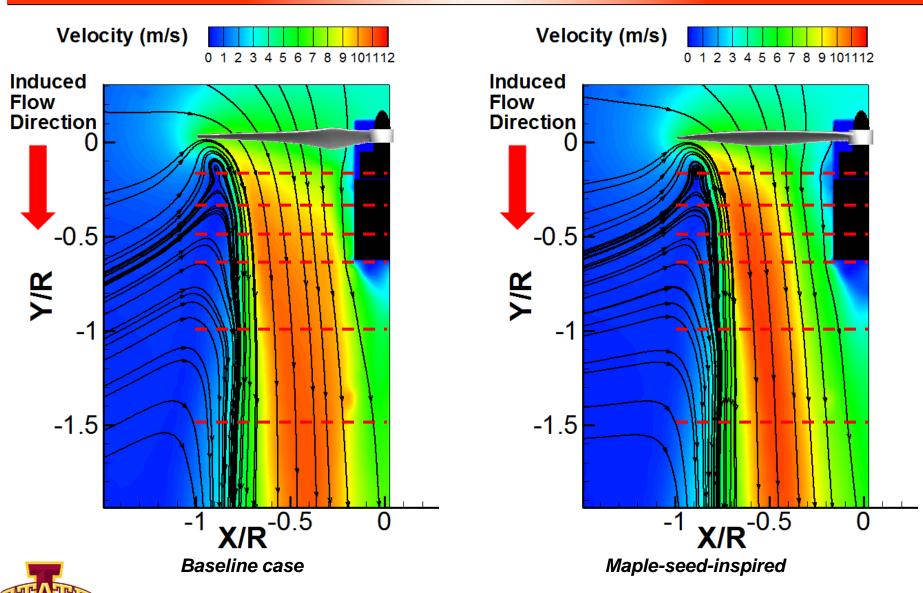




- Reduce total noise about 4 dB
- Noise reduction may be due to the decreased rotational speed of MSSP.
- The curved leading edge of the MSSP may reduce the velocity normal to the edge, therefore, reduce noise.
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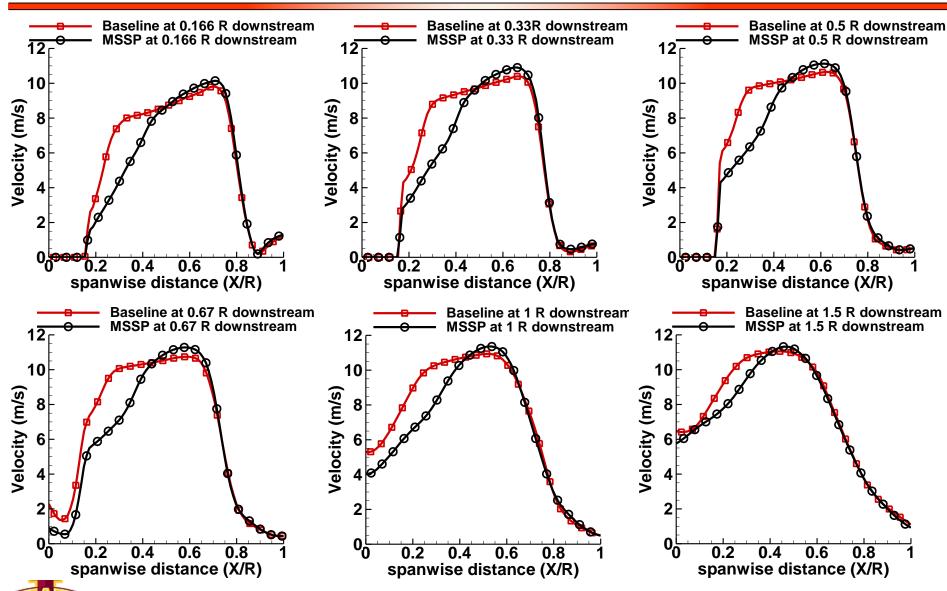
Free-run PIV Measurement Results





PIV Measurement Results

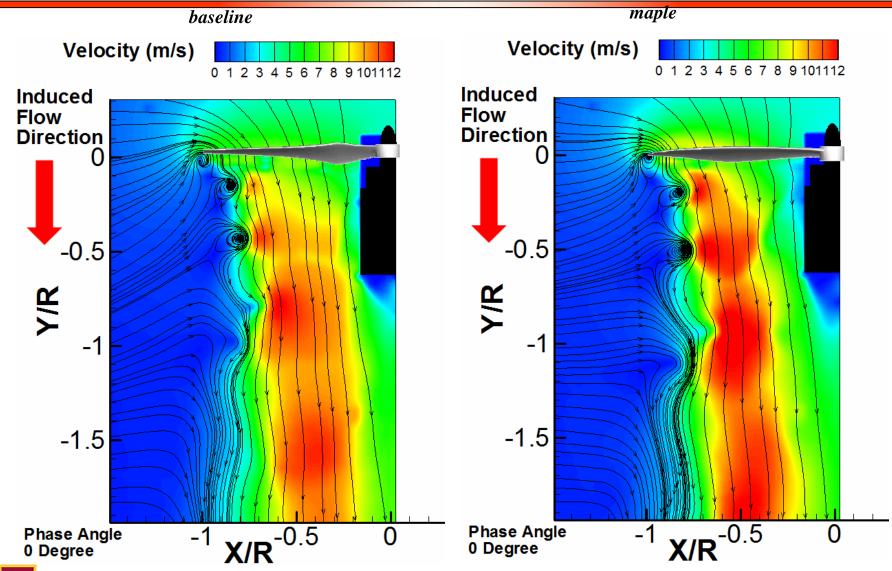




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Phase-locked PIV Measurement Results

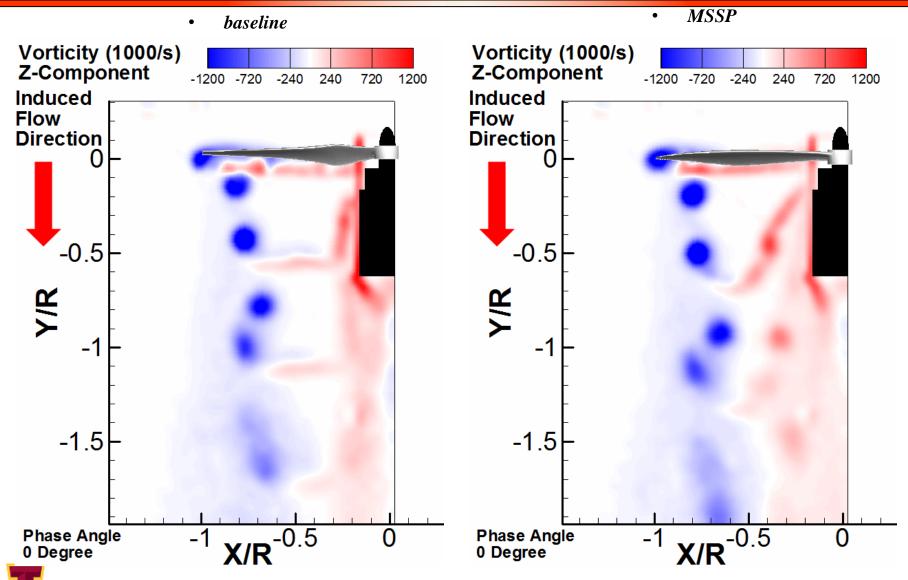






Phase-locked PIV Measurement Results





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Collaborators:
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Current postdocs & scholars: R. Waldman; Y. Liu, WW Zhou

Current Graduate Students: P. Premaratne (PhD). LX Li(PhD); Z. Ning; LQ Ma(PhD); LK Li(PhD); LY Gao(PhD);

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Former PhD Students:
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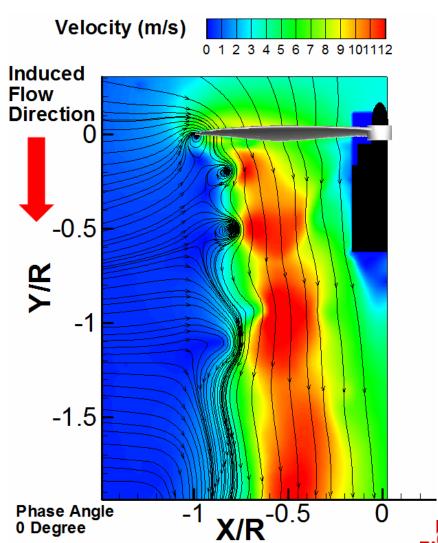








Thank you Very Much for Your Time! Questions?

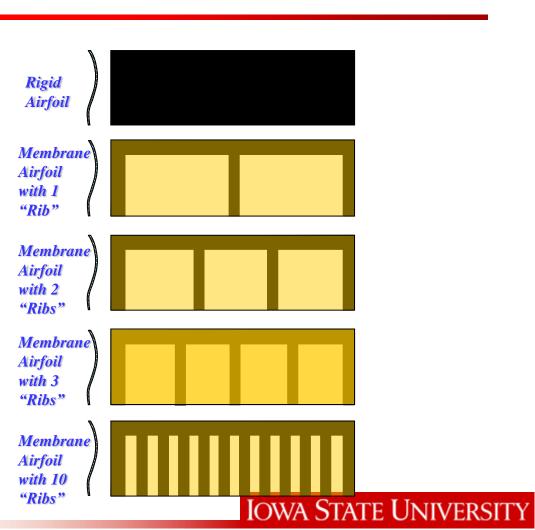




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Topic #2: Flexible Membrane Airfoils/Wings for Fixed-Wing MAV Applications







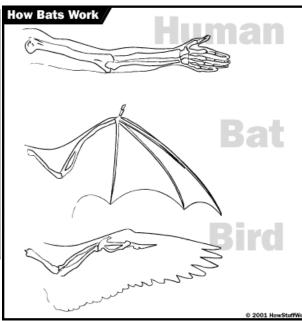
☐ Flexible Membranes—Bats, Flying Squirrels and Sugar Gliders



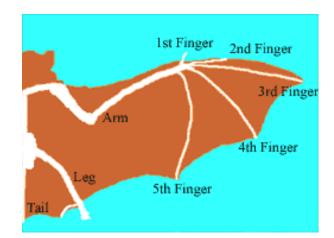




Bat







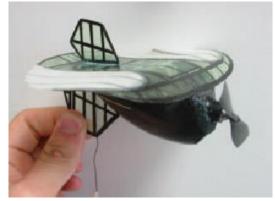


Objective of the Present Study



- Flexible membrane airfoils/wings are found to be able to adapt better to incoming flow to delay airfoil stall and have the potential for morphing to achieve enhanced agility and storage consideration compared to a rigid airfoil/wing.
- The majority of previous experimental studies on flexible membrane wings were conducted based mainly on total aerodynamic force and/or moment measurements.
- Very little in the literature can be found to investigate the flow behavior around flexible membrane airfoils as well as their effects on the overall aerodynamic performances of the membrane airfoils.
- Objectives of the present study:
 - To correlate aerodynamic force measurements and flow field measurements to elucidate underlying fundamental physics associated with the benefits of using flexible membrane airfoils at low Reynolds numbers
 - To investigate the effects of flexibility (or rigid) of membrane airfoils on their aerodynamic performance in order to explore/optimize design paradigms for the development of such non-traditional, bio-inspired flexible membrane wings/airfoils in MAV designs.

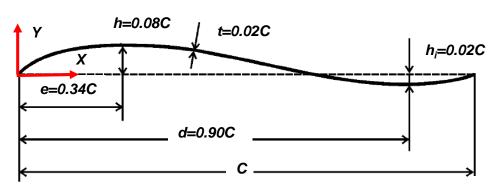




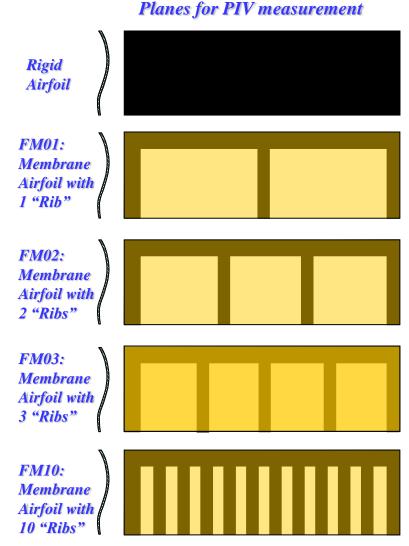
MAVs developed by the University of Florida team

Flexible Membrane Airfoils used in the Present Study





- The similar airfoil design is popular used for MAV applications.
- It is featured with a slight reflex in the trailing edge to reduce the strength of the inherent, negative pitching moment.
- The main frames are made of unidirectional carbon fiber to sustain bending moment as well as provide structural support.
- Latex sheet is bonded to the airfoil main frames to form the skins of the membrane airfoils.
- Different numbers of "ribs" are placed to adjust the flexibility of the membrane airfoils.



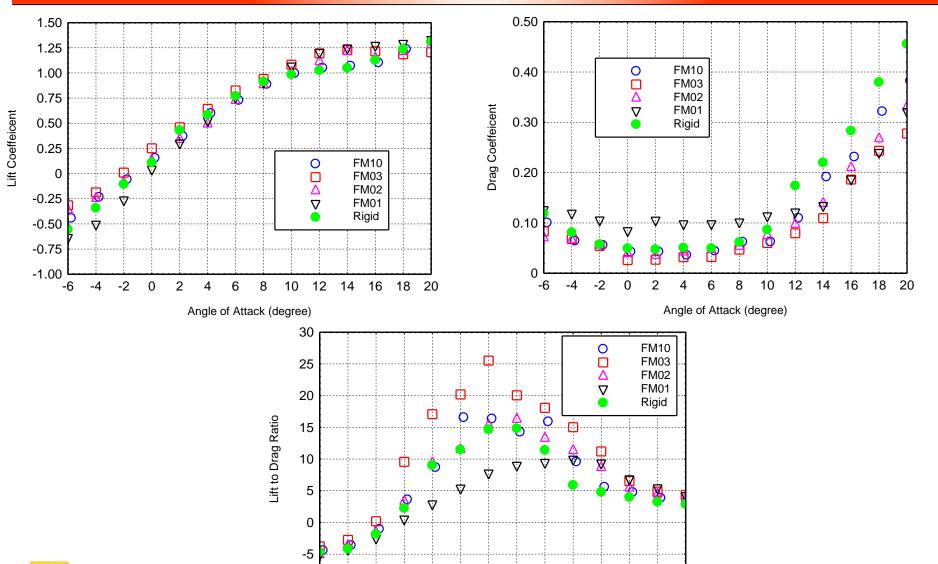


Aerodynamics Force Measurement Results

-10 -

-2





10

Angle of Attack (degree)

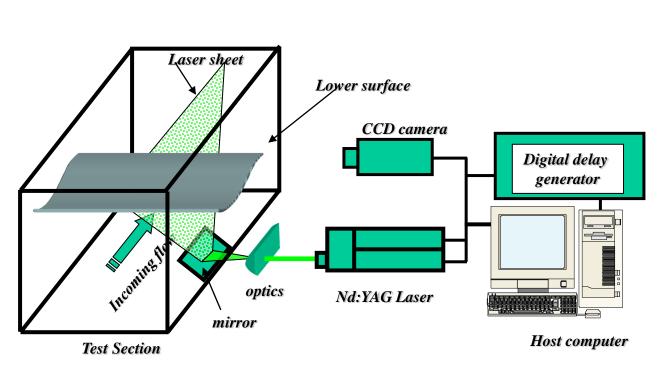
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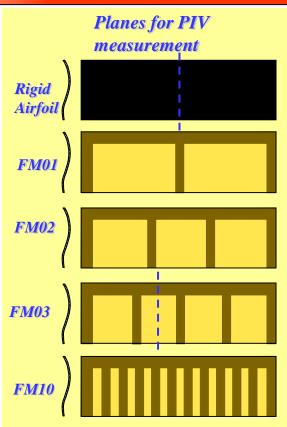


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Experimental Setup for PIV Measurements







Experimental conditions:

Incoming flow velocity: $U_{\infty} = 11.0 \text{ m/s}$, $\text{Re}_{C} = 70,000$

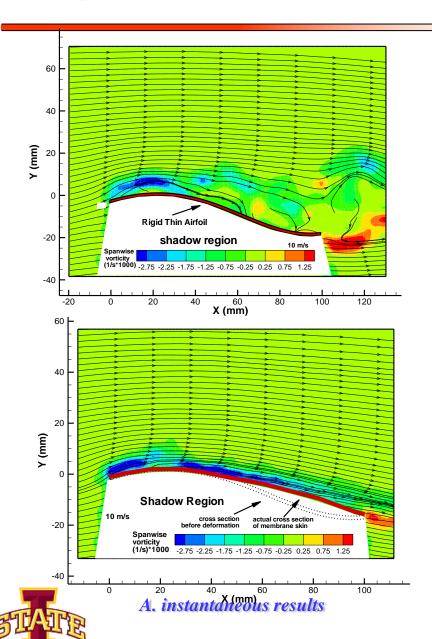
Turbulent intensity: ~1.0%

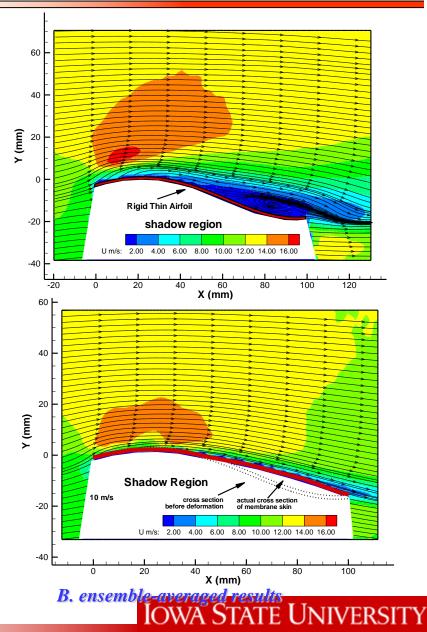
Angle of Attack: $\alpha = -6.0^{\circ} \sim 20.0^{\circ}$



□ Rigid Airfoil vs. Membrane Airfoil at AOA=10.0 degrees

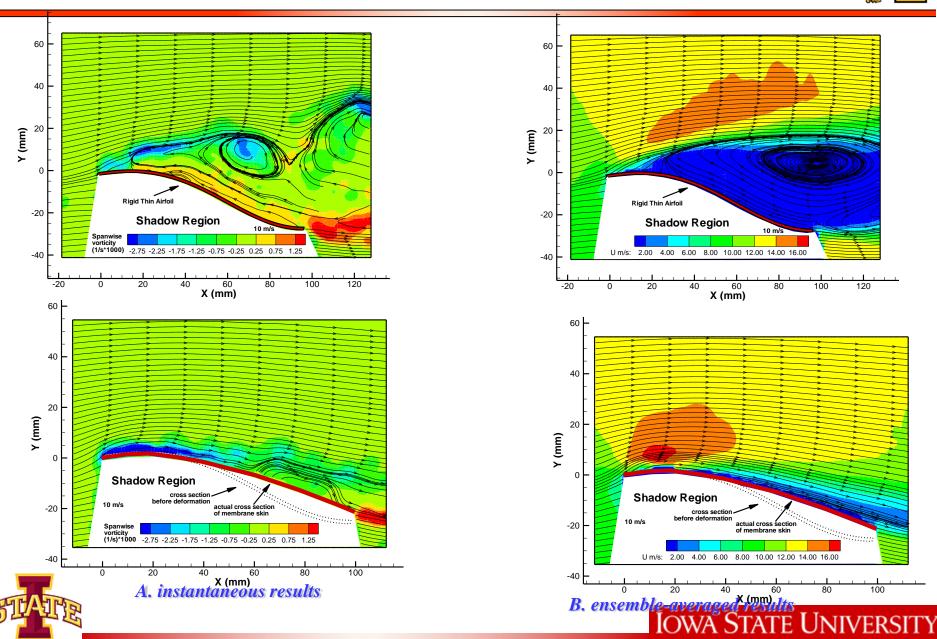






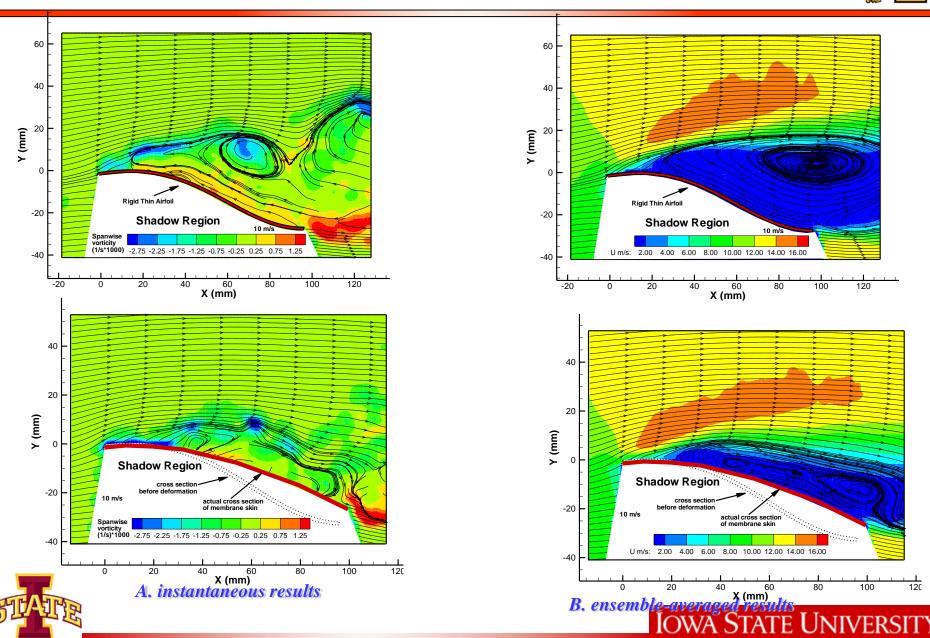
Rigid Airfoil vs. Membrane Airfoil at AOA=14.0 degrees





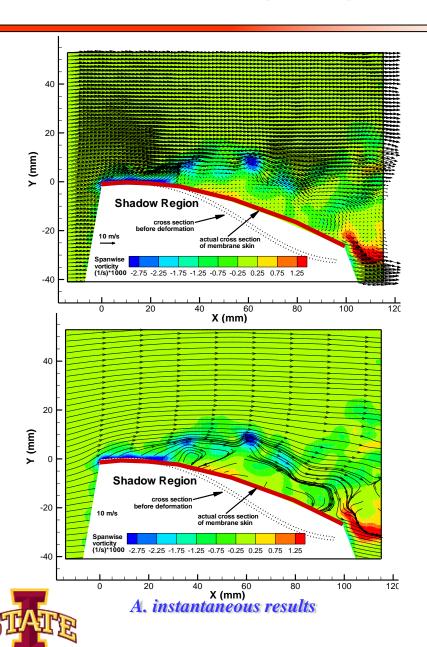
Rigid Airfoil vs. Membrane Airfoil at AOA=18.0 degrees

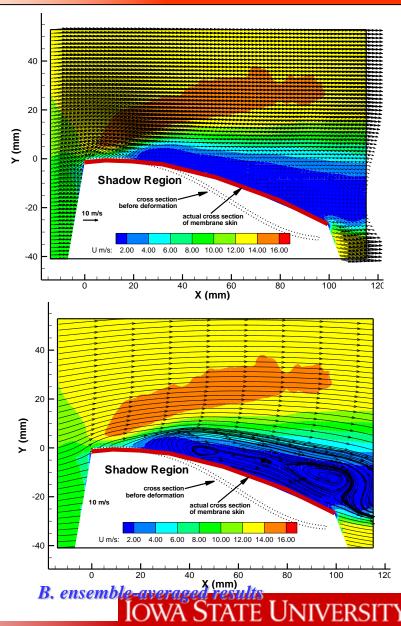




■ Membrane Airfoil, FM03, at A0A=18.0 degrees







■ Deformation of the Membrane Airfoil FM03



