Lecture # 11: Bio-inspired aerodynamics and Applications for Micro-Air-Vehicle (MAV) applications

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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.

\[ Re = \frac{\rho U L}{\mu} \]
Topic #1: An Experimental Study of a Bio-Inspired Corrugated Airfoil at Low Reynolds Numbers

- a. streamlined airfoil
- b. Flat plate
- C. corrugated dragonfly airfoil

Which one is better for MAVs? Why???
Bio-Inspired Corrugated Airfoil for MAV Applications

Which one is better for MAVs? Why???

- a. streamlined airfoil
- b. Flat plate
- c. corrugated dragonfly airfoil

Aerodynamic Force Measurement Results

\( \text{Re}=50,000 \)

\( \text{Re}=125,000 \)

(Murphy and Hu, 2010, Experiments in Fluids)
PIV Measurement Results
( AOA = 6.0 deg., Re=58,000)

A. instantaneous results

B. ensemble-averaged results
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 = 6.0 deg., Re=58,000)
PIV Measurement Results
( AOA = 12.0 deg., Re=58,000)

Spanwise vorticity (1000/s)

Velocity (m/s)

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

Spanwise vorticity (1000*1/s)

Velocity (m/s)

T.K.E.

Spanwise vorticity (1000*1/s)

Velocity (m/s)

T.K.E.
Summary

- Compared with the smooth-surfaced airfoil and flat plate, the **corrugated airfoil could generate higher lift and delay airfoil stall** to much higher angle of attack for low Reynolds number flight applications (Re<100,000).

- While aerodynamic performance of the smooth-surfaced airfoil and the flat plate would vary considerably with the changing of the Reynolds numbers, the aerodynamic performance of the **corrugated airfoil** was found to be almost insensitive to the chord Reynolds numbers.

- The detailed PIV measurements **elucidated underlying physics** about how and why corrugated airfoils could suppress large-scale flow separation and airfoil stall at low Reynolds numbers.
  - It was found that the **protruding corrugation corners** would act as boundary layer trips to promote the transition of the boundary layer from laminar to turbulent while remaining ‘attached’ to the envelope profile of the high speed streamlines.
  - The **valleys** of the corrugated cross section of the airfoil would trap unsteady vortex structures that help the boundary layer stay ‘attached’ by pulling high-speed flow into near wall regions.
  - It is by these two processes that the **corrugated airfoil** can overcome the adverse pressure gradient, thus, discourage large-scale flow separation and airfoil stall.
Topic #2: **Flexible Membrane Airfoils/Wings for Fixed-Wing MAV Applications**

- **Rigid Airfoil**
- Membrane Airfoil with 1 “Rib”
- Membrane Airfoil with 2 “Ribs”
- Membrane Airfoil with 3 “Ribs”
- Membrane Airfoil with 10 “Ribs”
Flexible Membrane Wings of Mammals – Bats, Flying Squirrels and Sugar Gliders

- Flying squirrel
- Bat
- Sugar glider

How Bats Work

Human
Bat
Bird

1st Finger
2nd Finger
3rd Finger
4th Finger
5th Finger
Arm
Leg
Tail

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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.
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.

(Tamai, Murphy and Hu, 2009, Journal of Aircraft)
- **Rigid thin airfoil** was found to stalls at AOA >10.0 degrees.
- **FM02, FM03 and FM10** were found to have very comparable or slightly larger lift coefficient compared with the rigid thin airfoil.
- The drag coefficients of **FM02, FM03 and FM10** were found to be significantly smaller than that of the rigid thin airfoil at relatively high angle of attack (i.e., AOA>10.0 degrees).
- The trailing edge of the **FM01** was found to be fluttering at AOA<10.0 degrees, therefore, **FM01** was found to have the worst aerodynamic performance at relatively low angle of attack.
- Surprisingly, **FM01** was found to have almost the best aerodynamic performance when the trailing edge fluttering disappeared at relatively high angles of attack (i.e., AOA>14.0 degrees)
As it is expected, FM10, which has the least flexibility among the tested flexible membrane airfoils, was found to have very similar aerodynamic performance as the rigid thin airfoil.

The flexible membrane airfoil FM03 was found to have the best aerodynamic performance (e.g., largest lift coefficient and smallest drag coefficient) among all the test airfoils with the lift-to-drag ratio being up to 25.5 at AOA=6.0 degrees.

The aerodynamic force measurement results revealed that the flexibility (or rigidity) of the membrane airfoil could affect their aerodynamic performance significantly.

It is important to choose a proper flexibility (or rigidity) of the membrane skins in order to achieve improved aerodynamic performance by using flexible membrane airfoils at Low Reynolds numbers for MAV applications.
**Experimental Setup**

**Experimental conditions:**

- **Incoming flow velocity:** $U_\infty = 11.0 \text{ m/s}$,  $\text{Re}_c = 70,000$
- **Turbulent intensity:** $\sim 1.0\%$
- **Angle of Attack:** $\alpha = -6.0^\circ \sim 20.0^\circ$
Rigid Thin Airfoil at AOA=6.0 degrees

A. instantaneous results

B. ensemble-averaged results
Rigid Thin Airfoil at AOA=10.0 degrees

A. instantaneous results

B. ensemble-averaged results
Membrane Airfoil, MF03, at AOA=10.0 degrees

A. instantaneous results

B. ensemble-averaged results
Rigid Thin Airfoil at AOA=14.0 degrees

A. instantaneous results

B. ensemble-averaged results
Membrane Airfoil, FM-03, at AOA=14.0 degrees

A. instantaneous results

B. ensemble-averaged results
Membrane Airfoil, FM03, at AOA=18.0 degrees

A. instantaneous results

B. ensemble-averaged results
Deformation of the Membrane Airfoil FM03

Membrane Airfoil with 3 “Ribs”
Concluding Remarks

• An experimental study was conducted to assess the benefits of using flexible membrane airfoils/wings at chord Reynolds number of $Re_c = 70,000$ for MAV applications compared with their rigid counterpart.

• The effects of the flexibility of the membrane airfoils on their aerodynamic performance were also assessed by adding different numbers of rigid “ribs” to the same membrane airfoil configuration to adjust the flexibility of the membrane skins of the airfoils.

• The measurement results elucidated that membrane airfoils/wings could provide better aerodynamic performance compared with their rigid counterpart due to following reasons:
  – membrane airfoils can change their camber shapes to adapt to incoming flows automatically to balance the pressure difference applied on the upper and lower surfaces of the airfoils, thereby, suppress large-scale flow separation on the airfoils.
  – The significant deformation of the flexible membrane skins at high angles of attacks can also result in the reduction of the effective angles of attack of the airfoils to delay airfoil stall.

• The measurement results also revealed that the flexibility (rigidity) of the membrane airfoils have a strong effect on their aerodynamic performance.
  – If the membrane airfoils are too flexible, trailing edge fluttering phenomena may occur, resulting in poor aerodynamic performance at relatively low angles of attack.
  – If the membrane airfoils are too rigid, it would limit the abilities of the membrane airfoils to adapt to incoming flows to suppress large-scale flow separation and delay airfoil stall, thereby, degrading the aerodynamic performance at relatively high angles of attack.
Topic #3: Unsteady Vortex Structures in the Wake of a Piezoelectric Flapping Wings
Flapping Mechanism for Flapping Wing MAVs and Nano-Air-Vehicles

- **Piezoelectric actuator**
  - Piezoelectric actuator–based flapping Mechanism
    - Compact in size
    - Simple structure
    - Much higher flapping frequency, \( f = 60\text{~}200\text{Hz} \)

### Mechanical flapping mechanism
- Bulky in size
- Structure complex
- Relatively low flapping frequency, \( f < 15 \text{ Hz} \)

### Fruit fly @50 ~ 150Hz
### Dragonfly @ 30 ~ 100 Hz

- **Side view**
  - Wing span, \( C = 50 \text{ mm} \)
  - Total length, \( L = 64 \text{ mm} \)

- **Global view**
  - \( c = 12.7 \text{ mm} \)
Dynamic Response of a Piezoelectric Flapping Wing

Sinusoidal AV voltage

Piezoelectric material

Flapping Amplitude (mm)

Applied Voltage (V)

Displacement (mm)

Phase Angle (deg.)

Linear curve fit
Measurement data

Sine wave fit
Measurement data
Experimental Setup

Two Kinds of PIV measurements:
- Unsynchronized PIV measurements
- Phase-locked PIV measurements

Test conditions:
- Chord length, $C=12.5\text{mm}$
- Flapping frequency, $f=60\ \text{Hz}$
- Flapping amplitude at wing tip, $A/C = 0 \sim 2.0$
- Incoming flow velocity, $V=0.5 \sim 10\ \text{m/s}$
- Chord Reynolds number, $Re = 500 \sim 10,000$
- Angle of Attack, $AOA = 0, 10, 20\ \text{deg.}$
Parameters used to characterize Flapping Wings

- **Non-dimensional flapping amplitude:**
  \[ h = \frac{A}{c} \]

- **Reduced flapping frequency:**
  \[ k = \frac{2\pi f c}{V_\infty} \]

- **Strouhal Number:**
  \[ Str = \frac{f A}{V_\infty} = \frac{k h}{2\pi} \]

- **Advance ratio:**
  \[ J = \frac{\text{Incoming flow velocity}}{\text{Wing tip velocity}} \]
  \[ = \frac{V_\infty}{4A f} = \frac{1}{4 \cdot Str} \]

- **Flapping flight regime:**
  - \( J > 1 \), flapping flight in quasi-steady regime
  - \( J < 1 \), flapping flight in unsteady regime

- **Advance ratio of the bumblebee, black fly and fruit fly in free flight:**
  - 0.66, 0.50, and 0.33 respectively
Vortex Structures in the Wakes of 2-D Oscillating Airfoils

(a). drag-producing wake

(b). Neutral wake

(c). Thrust producing wake
Unsteady flow structures @ different wing span locations

V=1.36 m/s, f=60Hz, A= 3.44 mm
(h=0.27;  k=3.52; J=1.70)

V=1.36 m/s, f=60Hz, A= 5.64 mm
(h=0.44;  k=3.52; J=1.03)

V=1.36 m/s, f = 60Hz, A= 8.20 mm
(h=0.65;  k=3.52; J=0.69 )
Unsteady Flow Structures @ Different Wingspan Locations

At 50% span location

At 75% span location

At 100% span location (wingtip)

$h = A/C = 1.3; \ k = 3.5, \ Str = 0.30, \ Re=1,400, \ J = 0.69$
Velocity Profiles @ Different Downstream Locations

\( \frac{h}{A/C} = 1.3; \ k = 3.5, \ Str = 0.30, \ J = 0.69 \)
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**

\[ V=1.36 \text{ m/s}, f=60\text{Hz}, A=8.20 \text{ mm} \ (h=0.65; \ k=3.52; \ J=0.69) \]
Dragonfly Flight

- They are some of 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

Image Courtesy: Bret Douglas
Video: David Attenborough – Life in the undergrowth
Experimental Setup

Two Kinds of PIV measurements:
- Unsynchronized PIV measurements
- Phase-locked PIV measurements
The Studied Configurations

- Effects of the phase angle differences between the tandem flapping wings:

  \[ \text{AoA} = 0 \; \phi = 0^\circ \]

  \[ \text{AoA} = 0 \; \phi = 180^\circ \]

  \[ \text{Amplitude [mm]} \]

  \[ \text{Phase Angle [\phi]} \]

  \[ \text{Hind-Wing} \]

  \[ \text{Fore-Wing} \]

  \[ \text{a. In-phase flapping mode} \]

  \[ \text{b. Anti-phase flapping mode} \]
The Studied Configurations

**Effects of the spacing between the tandem flapping wings:**

(a). \( S = 0.15C \)

(b). \( S = 0.50C \)

(c). \( S = 1.0C \)

(d). \( S = 1.5C \)

(e). \( S = 2.0C \)
Measurement Results for Anti-Phase flapping with $S = 0.15C$

Anti-Phase Flapping

50% Span

75% Span

100% Span

Anti-Phase Flapping
Measurement Results of In-Phase Flapping with $S=0.15C$

50% Span

75% Span

100% Span

In-Phase Flapping
**Time Averaged Measurement Results with S=0.15C**

100% Anti-Phase Flapping

75% Anti-Phase Flapping

50% Anti-Phase Flapping

+Vortex Trajectory

- Vortex Trajectory

High Speed Jet

**In-Phase Flapping**
Anti-phase flapping would generate more thrust compared with in-phase flapping.
Measurement Results for Anti-Phase flapping with $S = 2.0C$

Anti-Phase Flapping
Measurement Results for In-Phase Flapping with $S = 2.0C$

50% Span

75% Span

100% Span

In-Phase Flapping
Time Averaged Measurement Results with $S = 2.0C$
The difference in thrust generation between the anti-phase flapping and in-phase flapping would decrease as the spacing between the tandem wings increasing.
Thank you for your time!
Questions?