仿生與實驗室晶片導論- 2020

# Introduction to Biomimetics (II)

## 拍翼飛行仿生力學之研究

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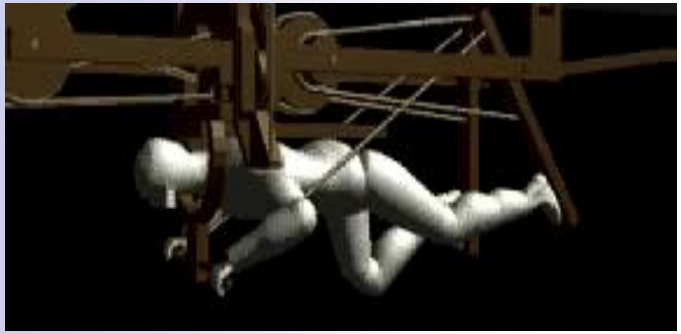
October 21st, 2020 @台灣大學應用力學研究所

# 拍翼機的先驅

## 達文西 (Leonardo Da Vinci, 1452-1519)



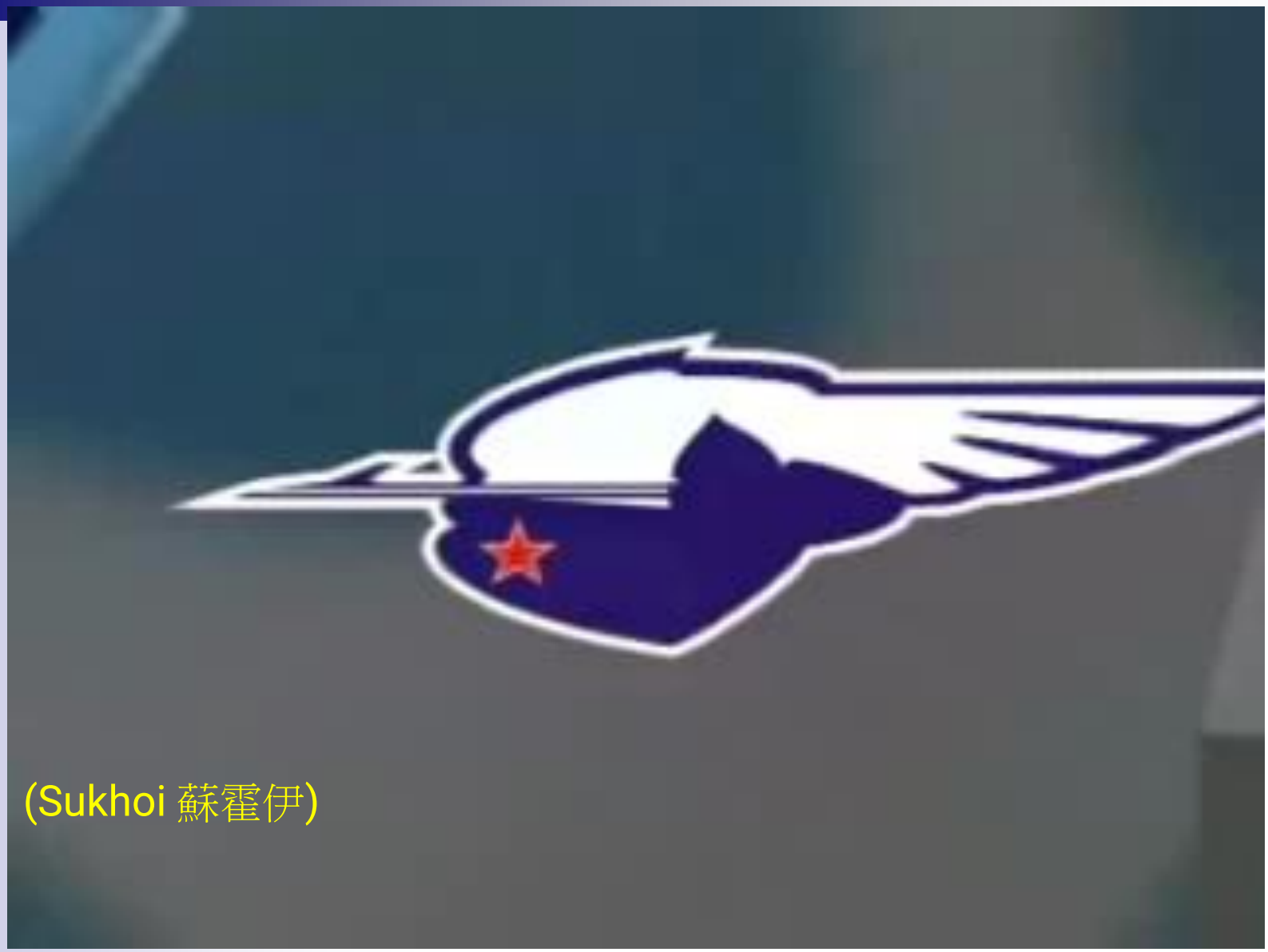
http://www.youtube.com/watch?v=bG52JmYfx2M

http://www.youtube.com/watch?v=aZI85oreTew

# 蘇凱SU-35 Air Show

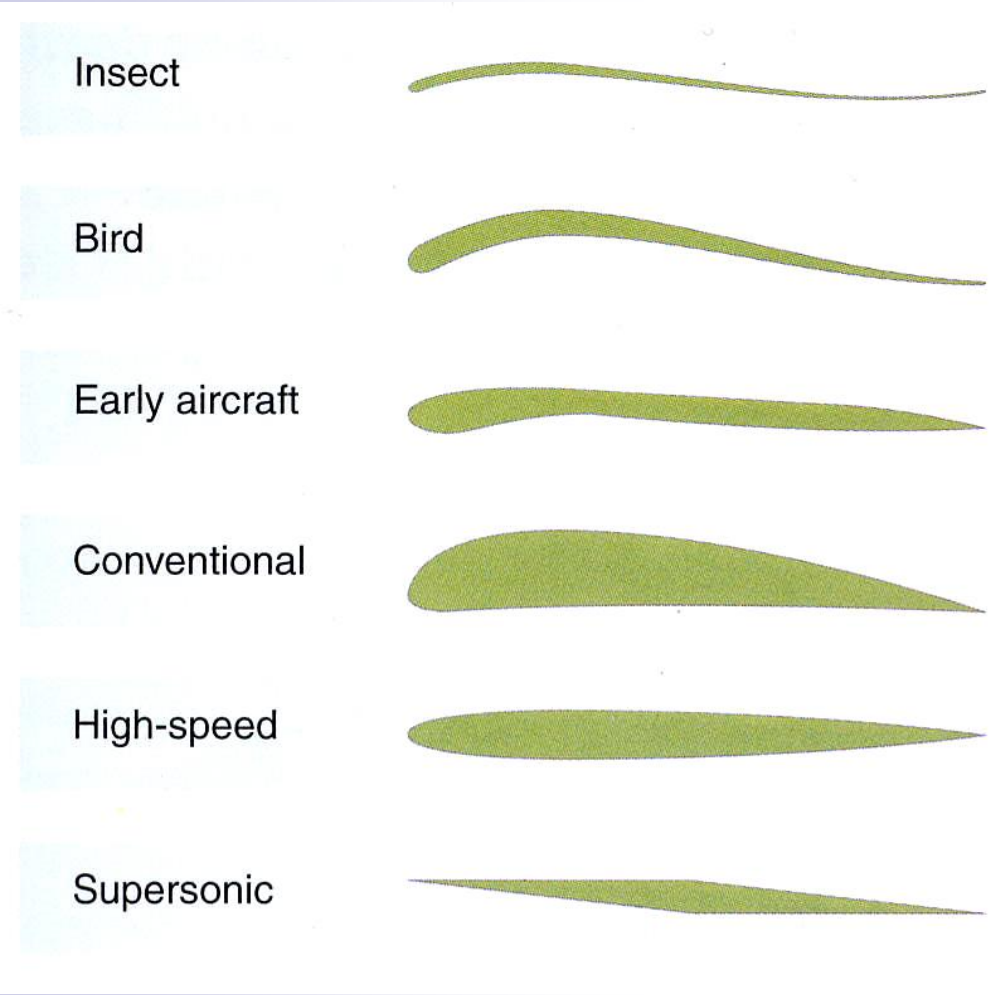
## Freefall Floating Flight & Falling Leaf Maneuver

https://www.youtube.com/watch?v=MA9AVXMiIDE

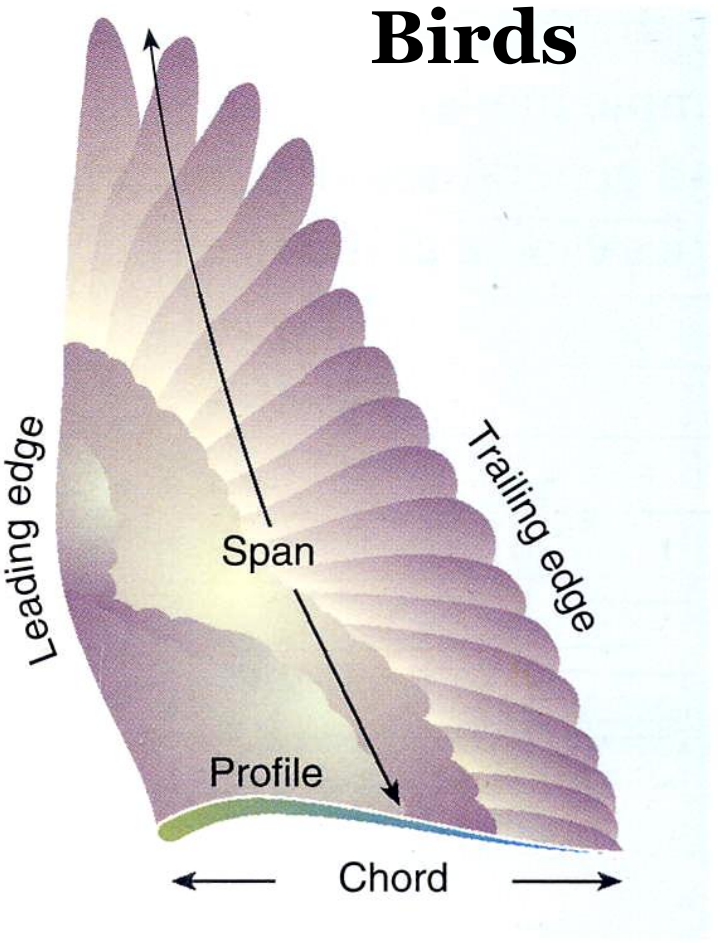


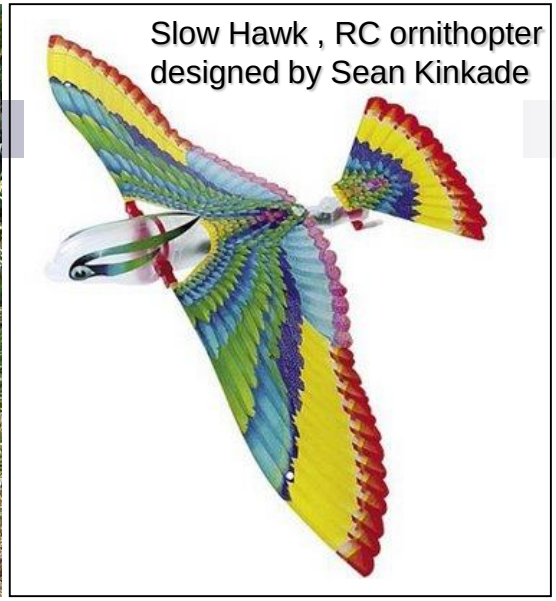
# Cross-sections of various flight creatures and airplanes

Burton, R., 1990, Bird Flight, England, ISBN 0-8160 2410-3




**Film from discovery**



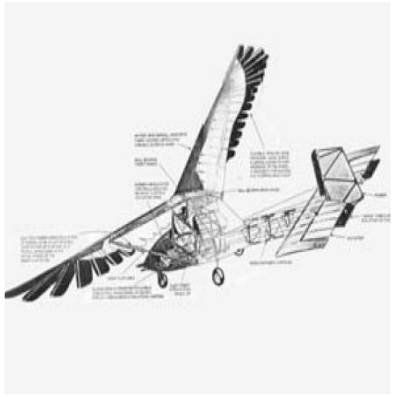

# The *UTIAS Ornithopter*


surface/volume

~ 1/*L*

# Aircraft with Flapping Wing

Edward P. Frost (1902)

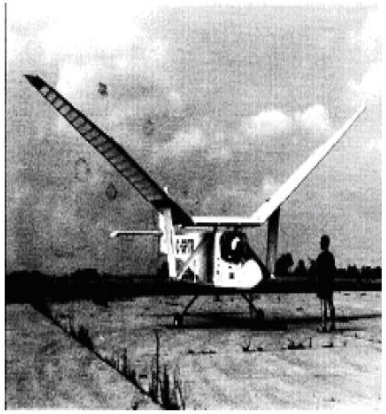


Emil Hartman (1959)

J. D. DeLaurier (2004)

Otto Lilienthal (1894)

Adalbert Schmid (1942)



J. D. DeLaurier (1997)


J. D. DeLaurier (2010)

| 1800 | 1900 | 1950 | 2000 |
|---|---|---|---|

# Snowbird- University of Toronto (2010)

https://www.youtube.com/watch?v=0E77j1imdhQ

# Animal Locomotion?
# Maneuvering Flight

**MAV** (micro aerial vehicle)

**AUV** (autonomous underwater vehicle)

**ROV** (remotely operated vehicle)

# Micro Aerial Vehicle (MAV)

Table 1 MAV design requirements

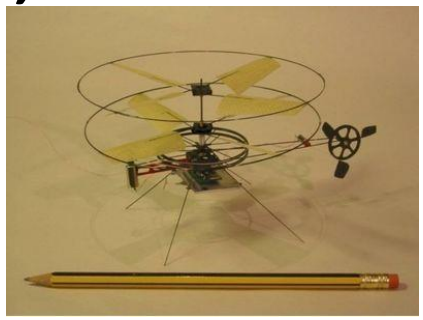
| Specification | Requirements | Details |
|---|---|---|
| Size | <15.24 cm | Maximum dimension |
| Weight | ~100 g | Objective GTOW |
| Range | 1 to 10 km | Operational range |
| Endurance | 60 min | Loiter time on station |
| Altitude | <150 m | Operational ceiling |
| Speed | 15 m/s | Maximum flight speed |
| Payload | 20 g | Mission dependent |
| Cost | $1500 | Maximum cost |

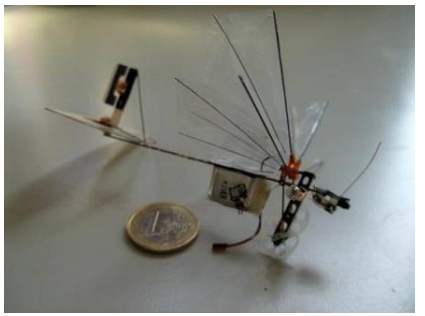
- **Max dimension: 15 cm**

  **Nominal flight speed: 10 m/s**

  **Reynolds number regime: $10^5$ or lower**

  ⇒ **monitoring, surveillance, assessment…**



- **Fixed wing**
- **Rotary wing**
- **Flapping wing**

# 仿生拍撲翼微飛行器

MAV 定義 (DARPA, 1997) :

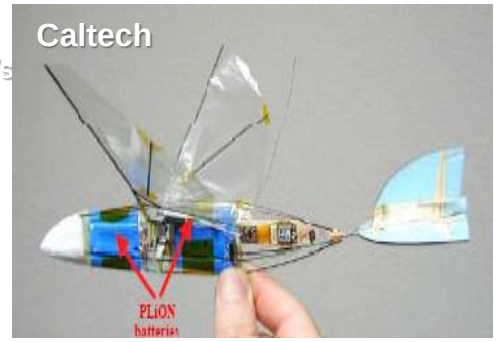
1. 尺寸 < 15 cm

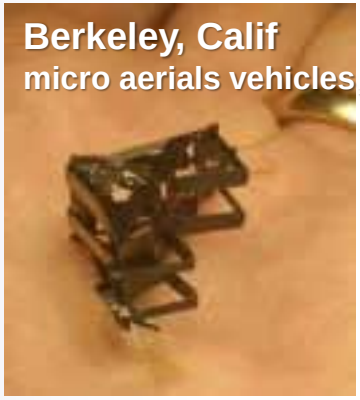
2. 飛行距離: 10 km

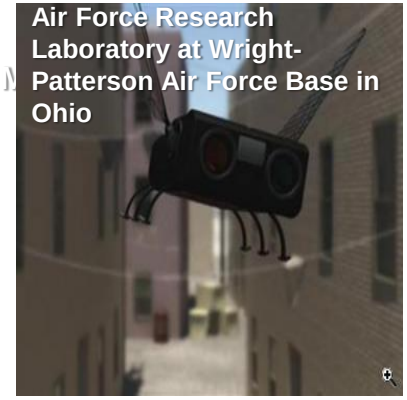
3. 飛行速度: 30 m/s

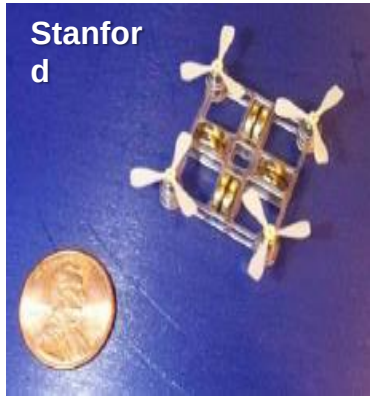
4. 飛行時間 > 20 min





# Nature- News and Views (June, 2013)

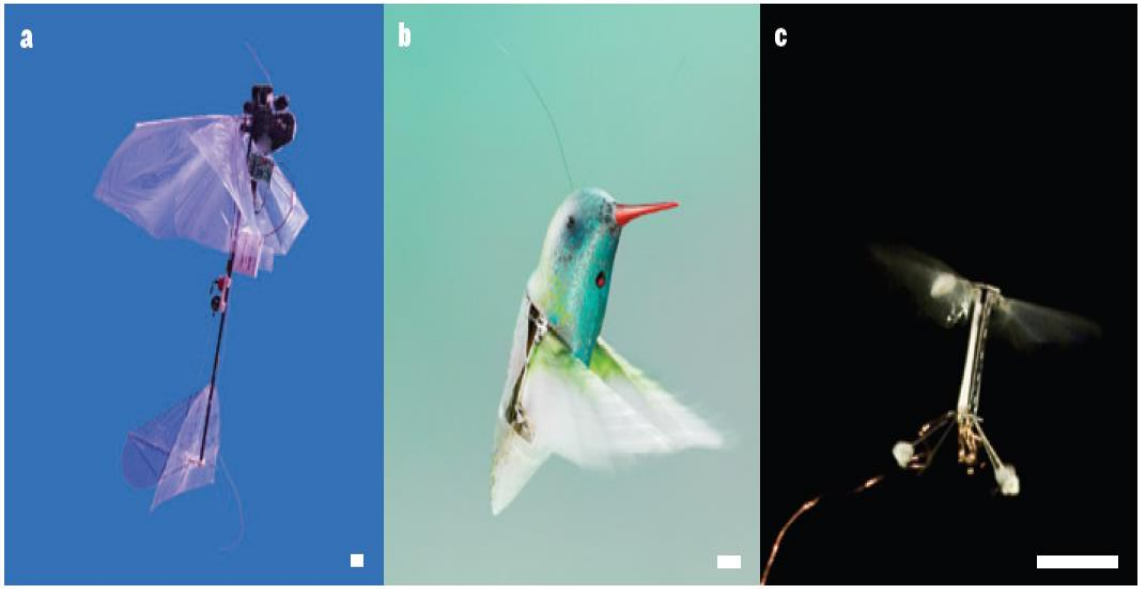
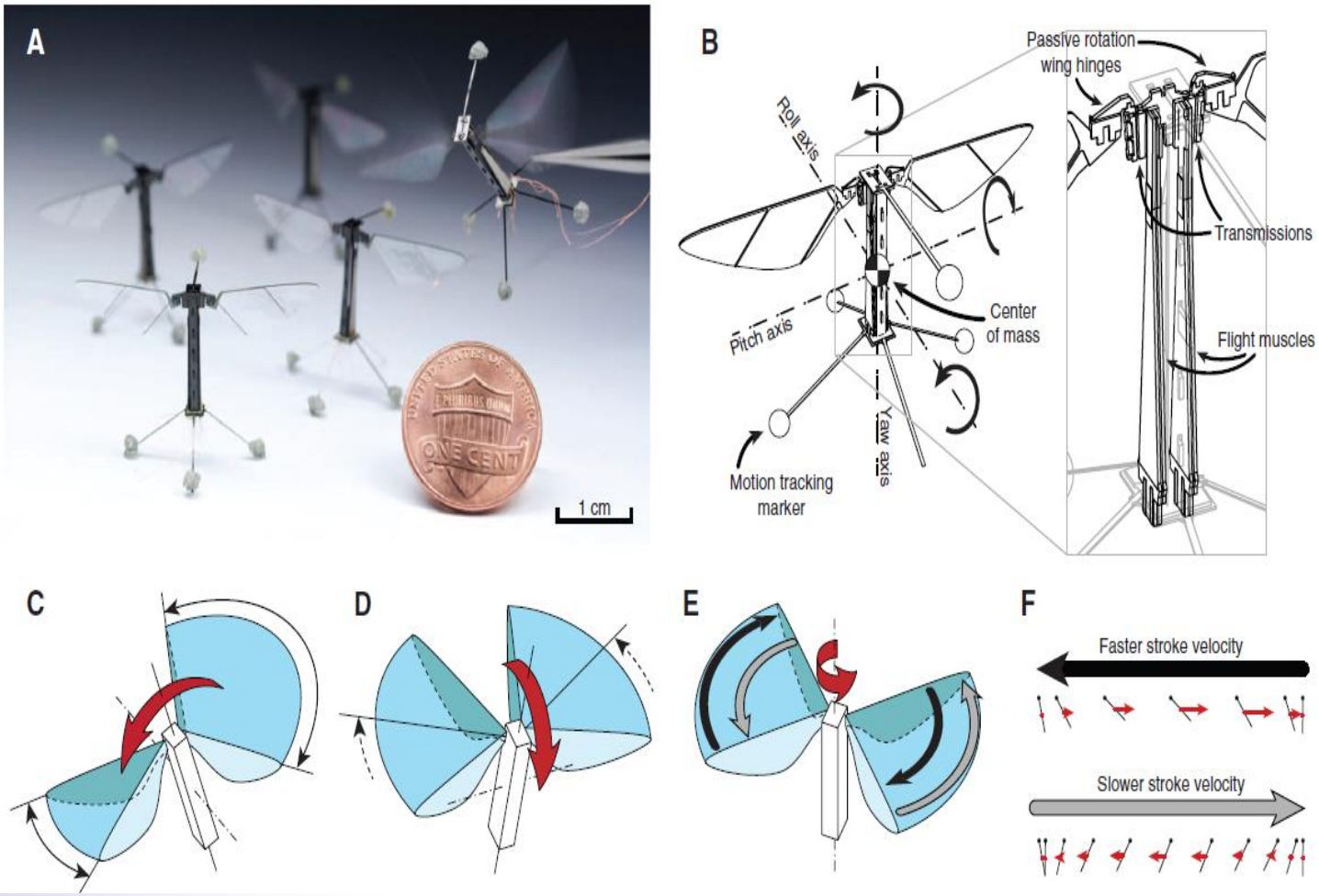



**Figure 1 | Winged victories.** Three successive iterations of miniaturized robots that each mimic certain aspects of animal hovering flight. **a**, The passively stable DelFly[7] hovers like an insect that is controlled by its tail. **b**, The tailless Nano Hummingbird[8] is stabilized by an on-board autopilot, which controls the wings' angle in a way analogous to that seen in real hummingbirds. **c**, Ma and colleagues' robot fly[1], shown here on its maiden flight, is controlled by a tether that provides modulated power to each flight 'muscle' of the wing. Scale bars, 10 millimetres (estimated).

**Controlled Flight of a Biologically Inspired, Insect-Scale Robot**

Kevin Y. Ma *et al.*

*Science* **340**, 603 (2013);
DOI: 10.1126/science.1231806




Roll Pitch Yaw

# Robot insect

https://www.youtube.com/watch?v=s0ONv5DZA7Y

# Design, aerodynamics, and vision-based control of the DelFly

**G.C.H.E. de Croon, K.M.E. de Clercq, R. Ruijsink, B. Remes, and C. de Wagter**
Aerospace Software and Technologies Institute, Technical University of Delft

Rotterdamseweg 380, 2629 HG, Delft, the Netherlands

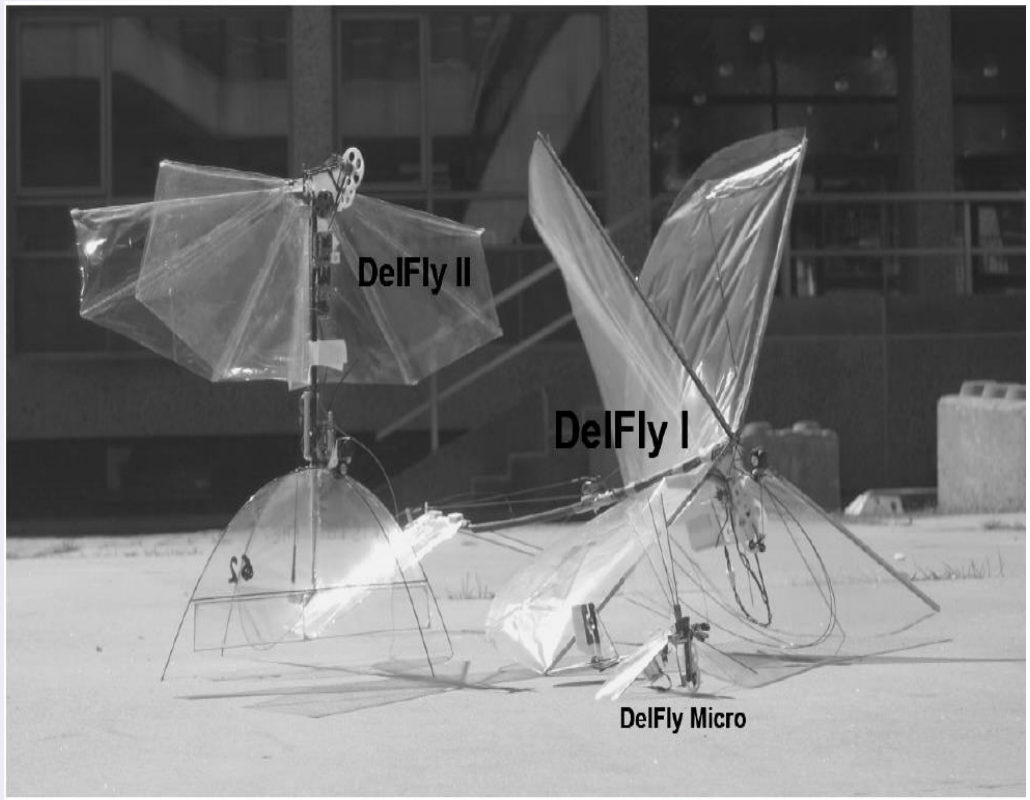



**Figure 1.** DelFly I (50 cm span, 21.00g), DelFly II (28 cm span, 16.07g) and DelFly Micro (10 cm span, 3.07g).

# Crank mechanism

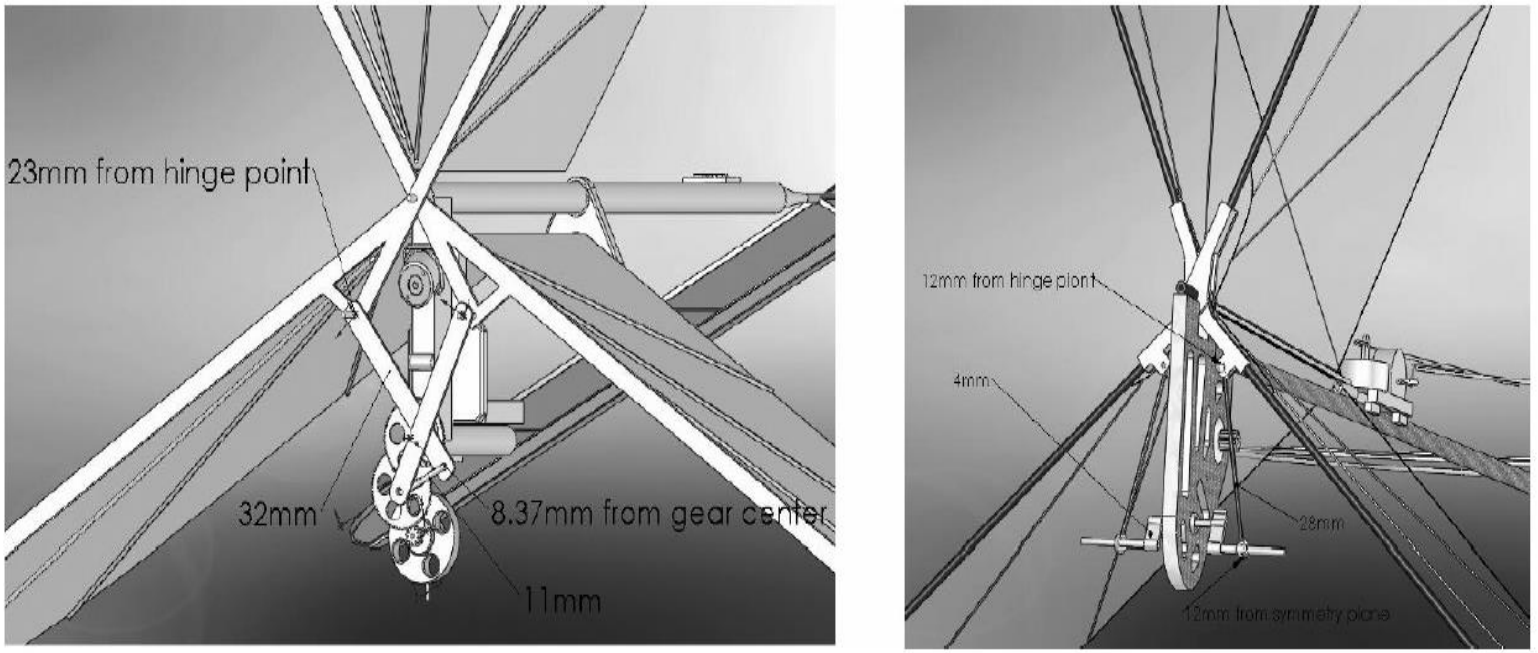
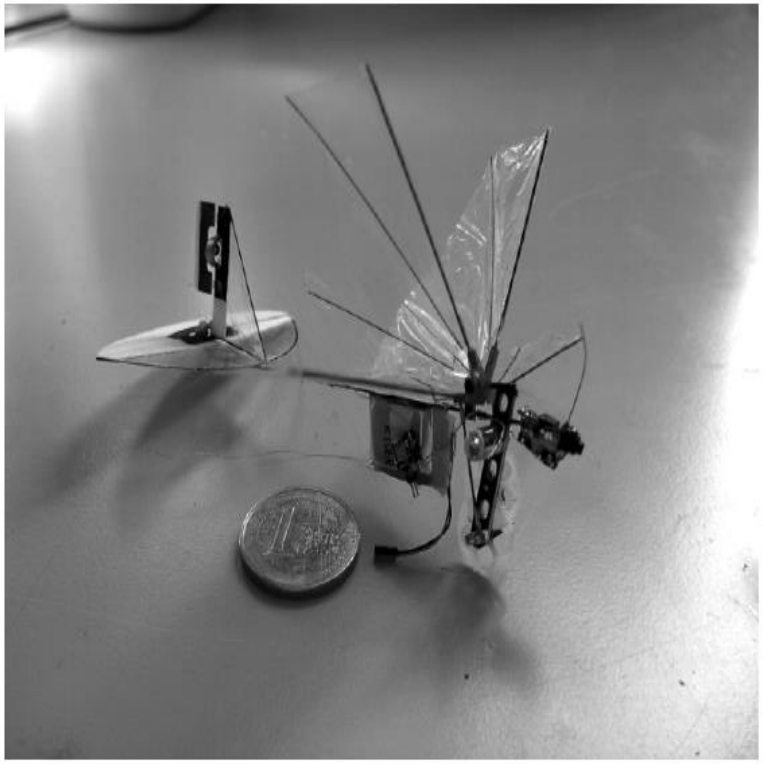



**Figure 2.** Schematics of the crank mechanism of DelFly I (left) 20 and DelFly II (right).

# DelFly II


https://www.youtube.com/watch?v=b

# DelFly Micro



| Total mass | 3.07 gr |
|---|---|
| Battery | 1.00 gr |
| Camera and transmitter | 0.40 gr |
| Motor | 0.45 gr |
| Receiver | 0.20 gr |
| Actuators | 0.50 gr |
| Rest | 0.52 gr |

**Figure 27.** Left: DelFly Micro next to a Euro coin. Right: Mass of the parts.

# DelFly Micro

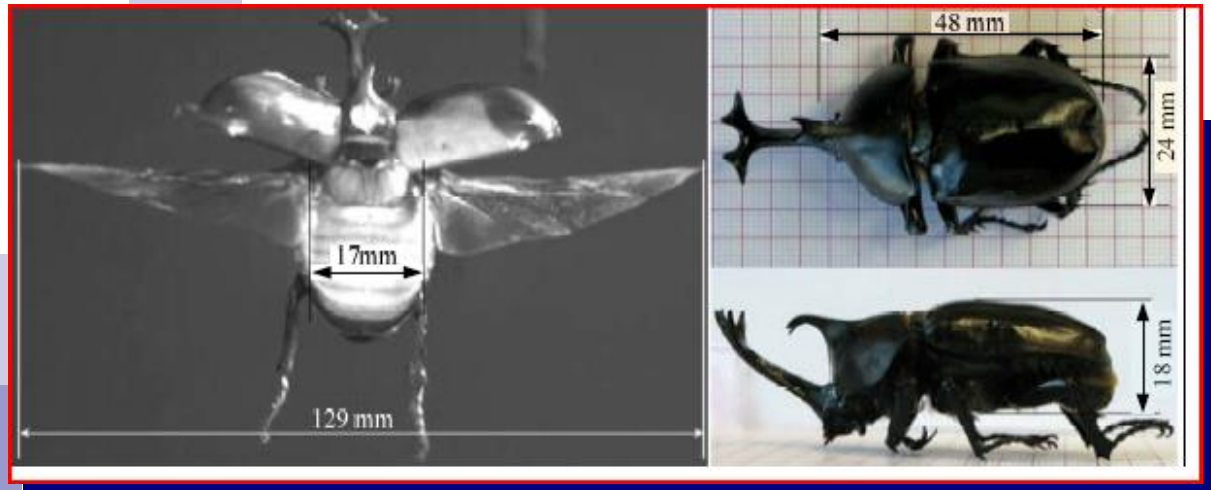
https://www.youtube.com/watch?v=L17

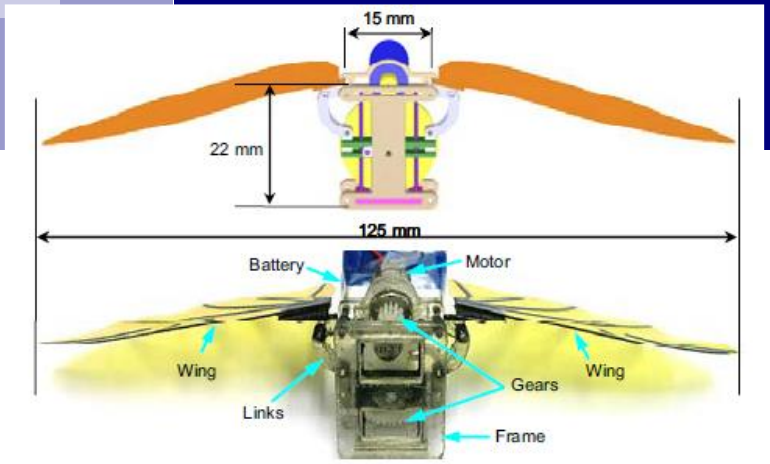
# The Tailless Nano Hummingbird

Nano Hummingbird
by AeroVironment Inc.
(Keennon et al., 2012)
weight 19 g
wingspan 16.5 cm
endurance 4-11 min

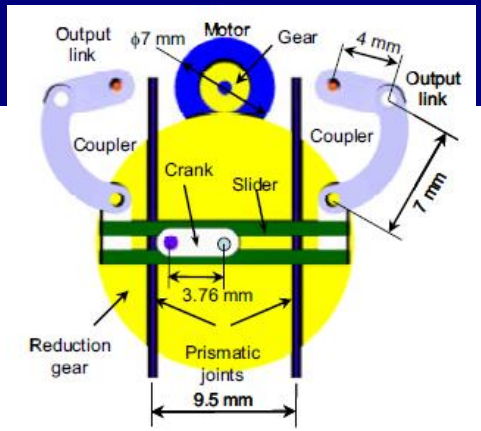
https://www.youtube.com/watch?v=SgxtIPIDBnY

Quoc Viet Nguyen *et al*. (2009) 製作出仿甲蟲（beetle); Frequency =17 Hz




仿甲蟲之撲翼飛行器




撲翼驅動機構

Journal of Bionic Engineering 7 (2010) 77–86

# Festo—Smart Bird (2011)

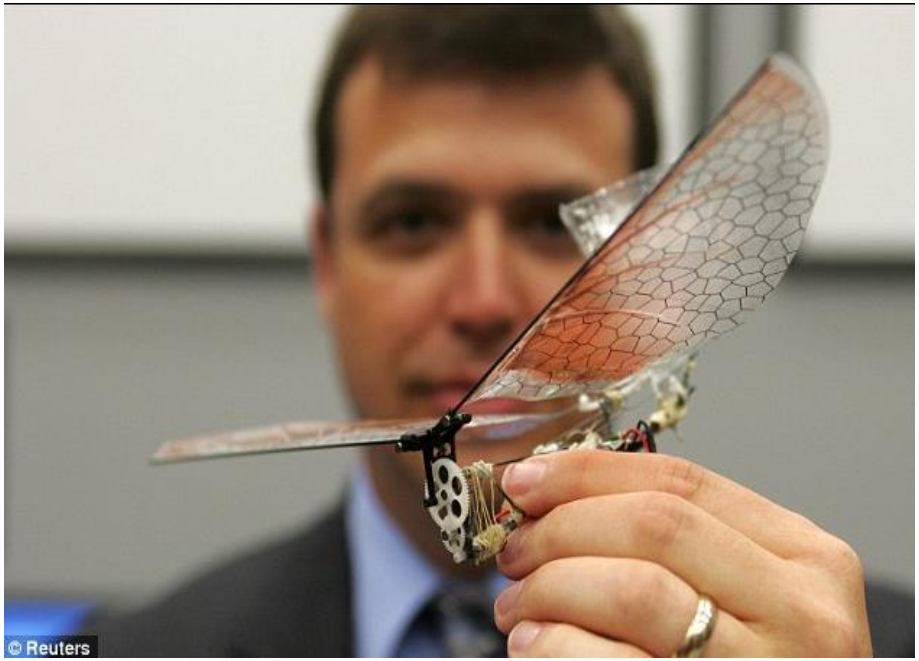

https://www.youtube.com/watch?v=nnR8fDW3Ilo

# Festo—Bionic Opter (2013)


https://www.youtube.com/watch?v=nj1yhz5io20

# Micro-machines (2011)

- The Micro Air Vehicles (MAVs) are being developed at Wright-Patterson Air Force Base in Dayton, Ohio.

# Micro Aerial Vehicles (2020)


Taha, H. E., Kiani, M., Hedrick, T. L., & Greeter, J. S. (2020). Vibrational control: A hidden stabilization mechanism in insect flight. *Science Robotics*, *5*(46).
影片連結: https://twitter.com/SciRobotics/status/1311682339194404866?s=06

de Croon, G. (2020). Flapping wing drones show off their skills. *Science Robotics*, *5*(44).
影片連結: https://twitter.com/SciRobotics/status/1287749670941478915?s=06

Chang, E., Matloff, L. Y., Stowers, A. K., & Lentink, D. (2020). Soft biohybrid morphing wings with feathers underactuated by wrist and finger motion. *Science Robotics*, *5*(38).
影片連結: https://twitter.com/SciRobotics/status/1218194559689220103?s=06

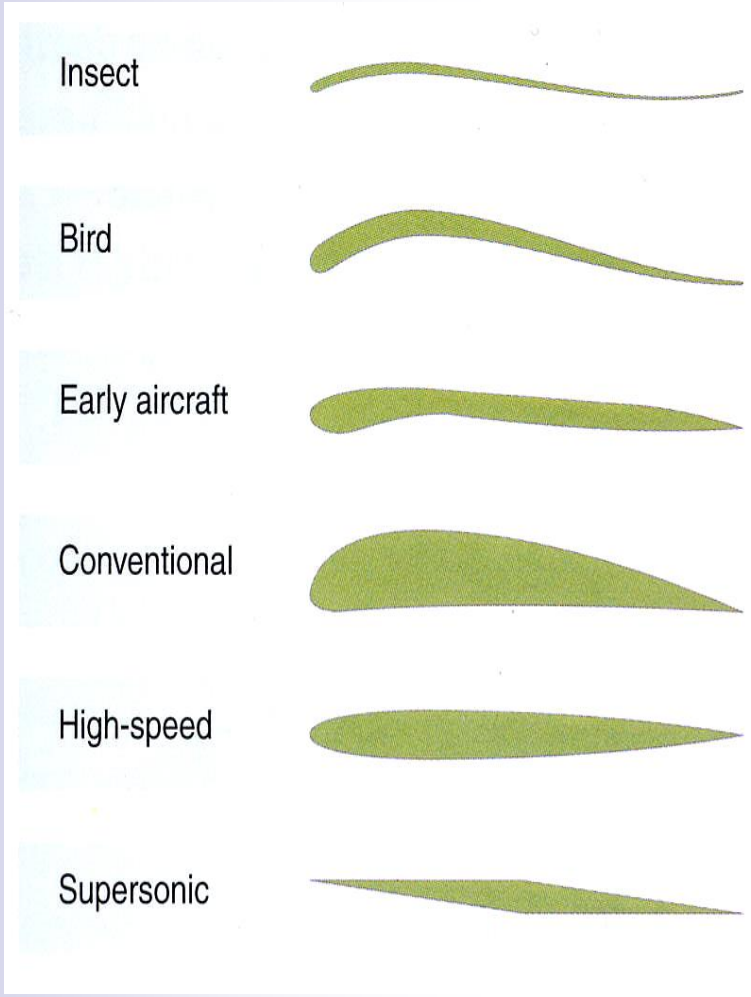
Usherwood, J. R., Cheney, J. A., Song, J., Windsor, S. P., Stevenson, J. P., Dierksheide, U., ... & Bomphrey, R. J. (2020). High aerodynamic lift from the tail reduces drag in gliding raptors. *Journal of Experimental Biology*, *223*(3).
影片連結: https://www.youtube.com/watch?v=2sh8_3-R90I&feature=youtu.be&ab_channel=naturevideo

# Biomimetics work in

## Beam Lab., NTU

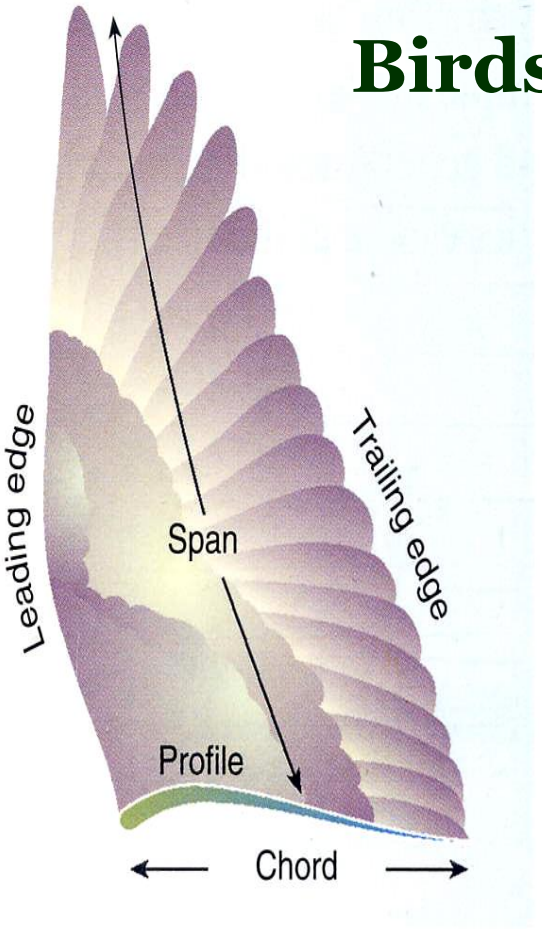
# Cross-sections of various flight creatures & airplanes

Burton, R., 1990, Bird Flight, England, ISBN 0-8160 2410-3




**Film from discovery**

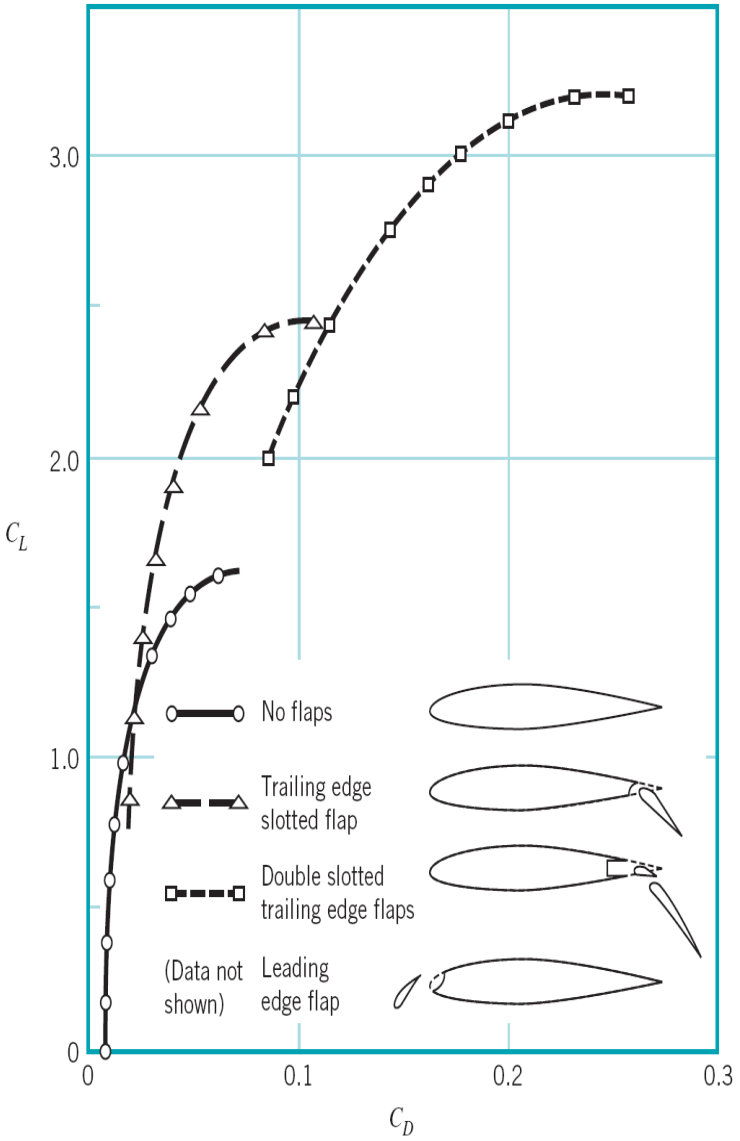
**Birds**



# Lift Control Devices

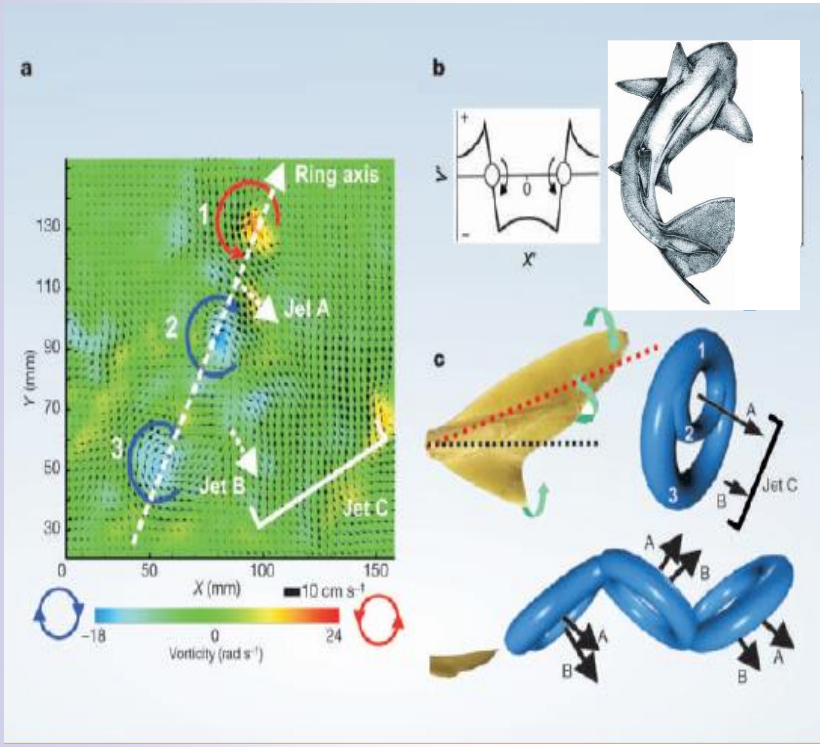


- To generate necessary lift during the relatively low-speed landing and takeoff procedures, the airfoil shape is altered by extending special flaps on the front and/or rear portion of the wing.
- Use of the flaps considerably enhances the lift, although it is at the expense of an increase in the drag

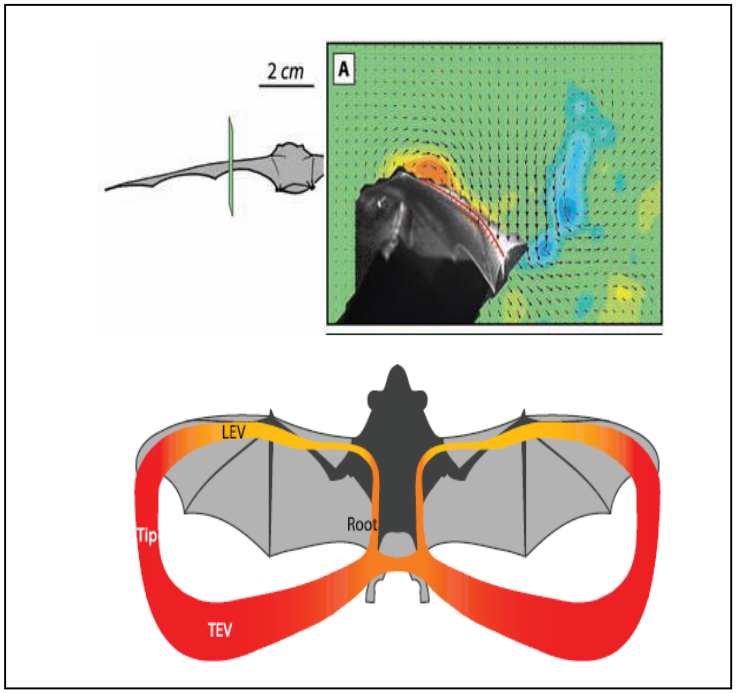


# 仿生學相關之學術研究

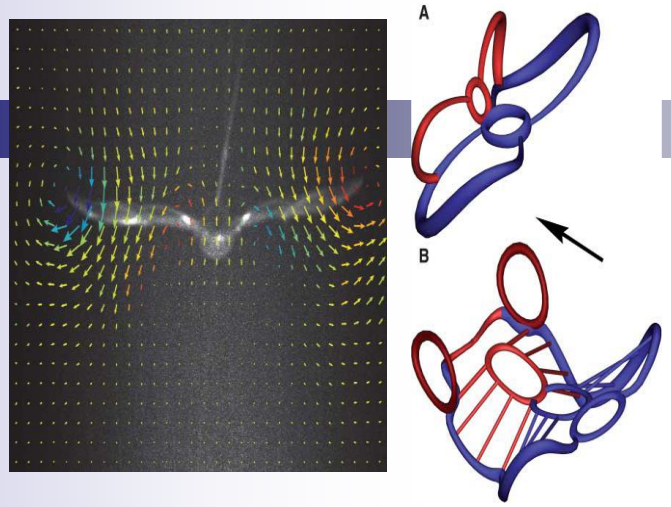
## (Biophysics and **Biomechanics** of animal locomotion)




鯊魚尾鰭推進 (*Nature*, 2004)

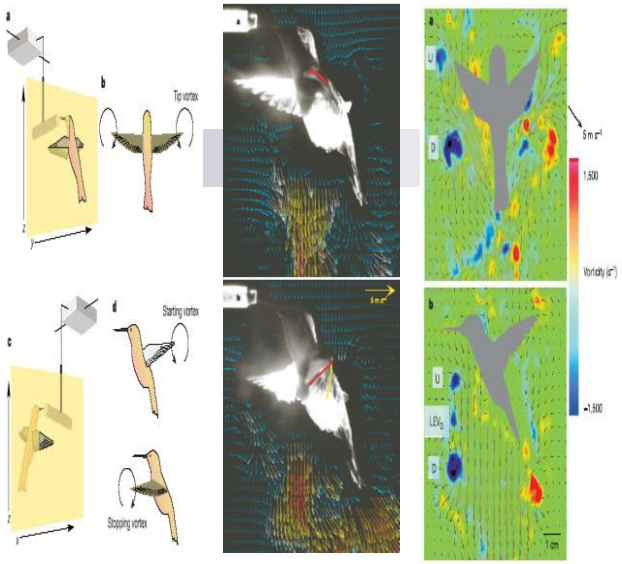



蝙蝠之翼前緣渦升力 (*Science*, 2008)



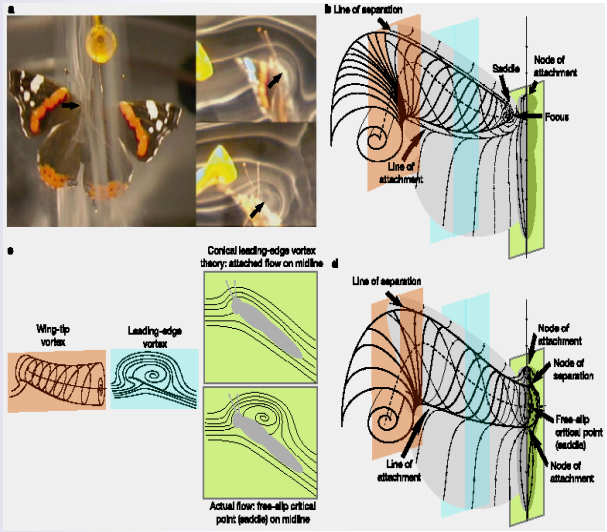

蝙蝠之複雜尾流結構

(*Science*, 2007)



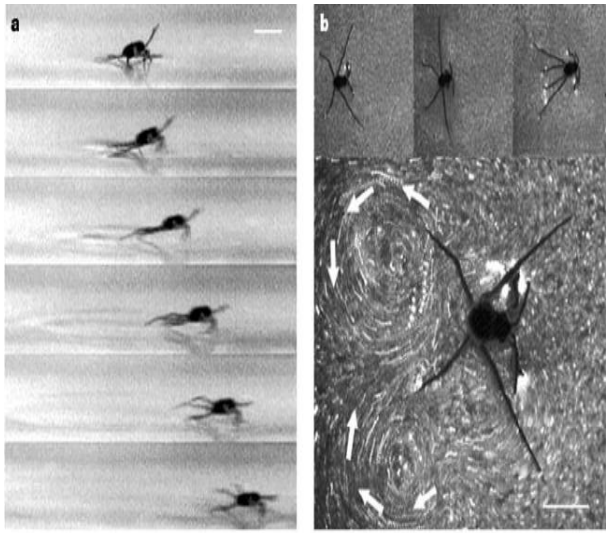

蜂鳥撲翼懸停飛行

( *Nature*, 2005 )




蝴蝶撲翼飛行

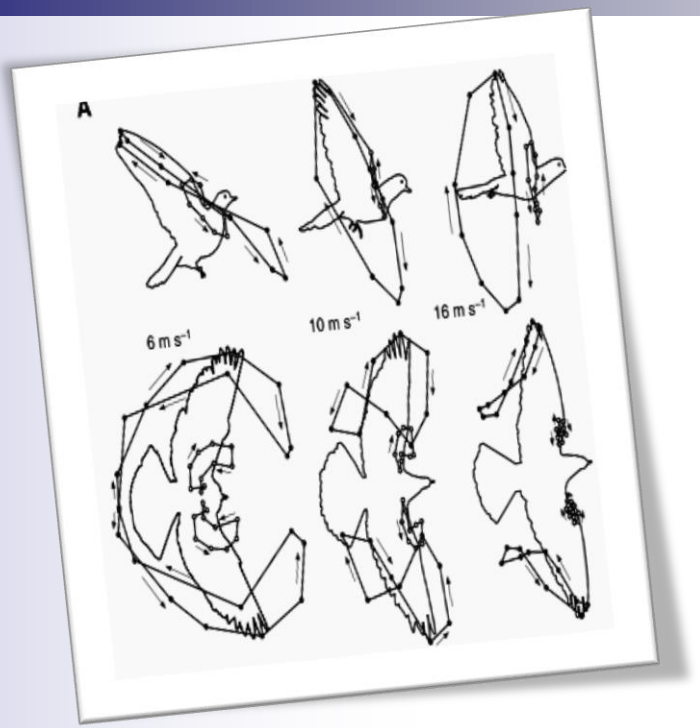
(*Nature*, 2002)



水黽水面推進

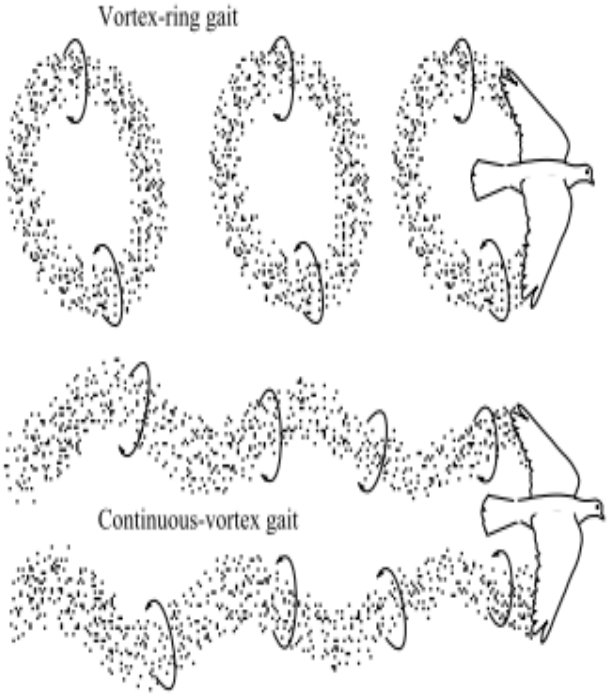
(*Nature*, 2003)

# 鳥類飛行力學

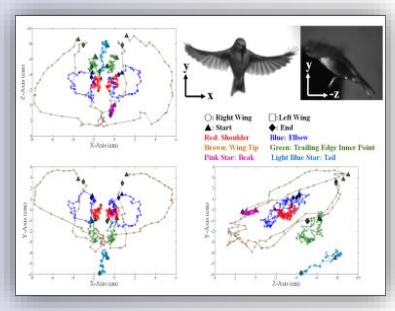


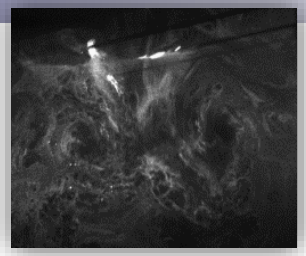

Kinematics

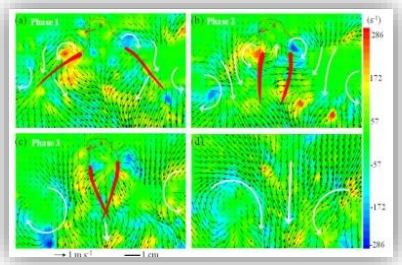
Aerodynamics

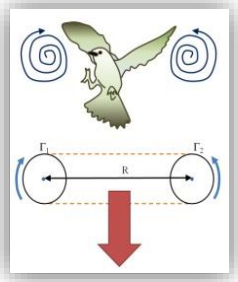


# Research Frame for NSC Projects





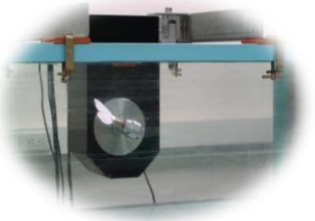




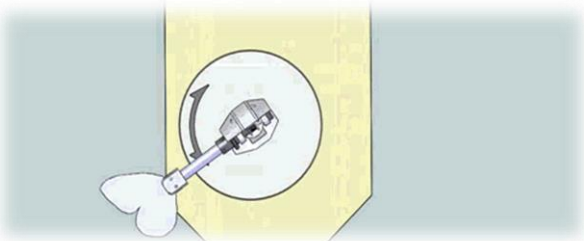
**Flight Mechanics & Biophysics** (2008-2014)

Observation, Measurement, Analysis (*Exp. & Simul.*) (2005-2014)

Artificial Design & Test (2013-2024)



**Biomimetic Vehicles**



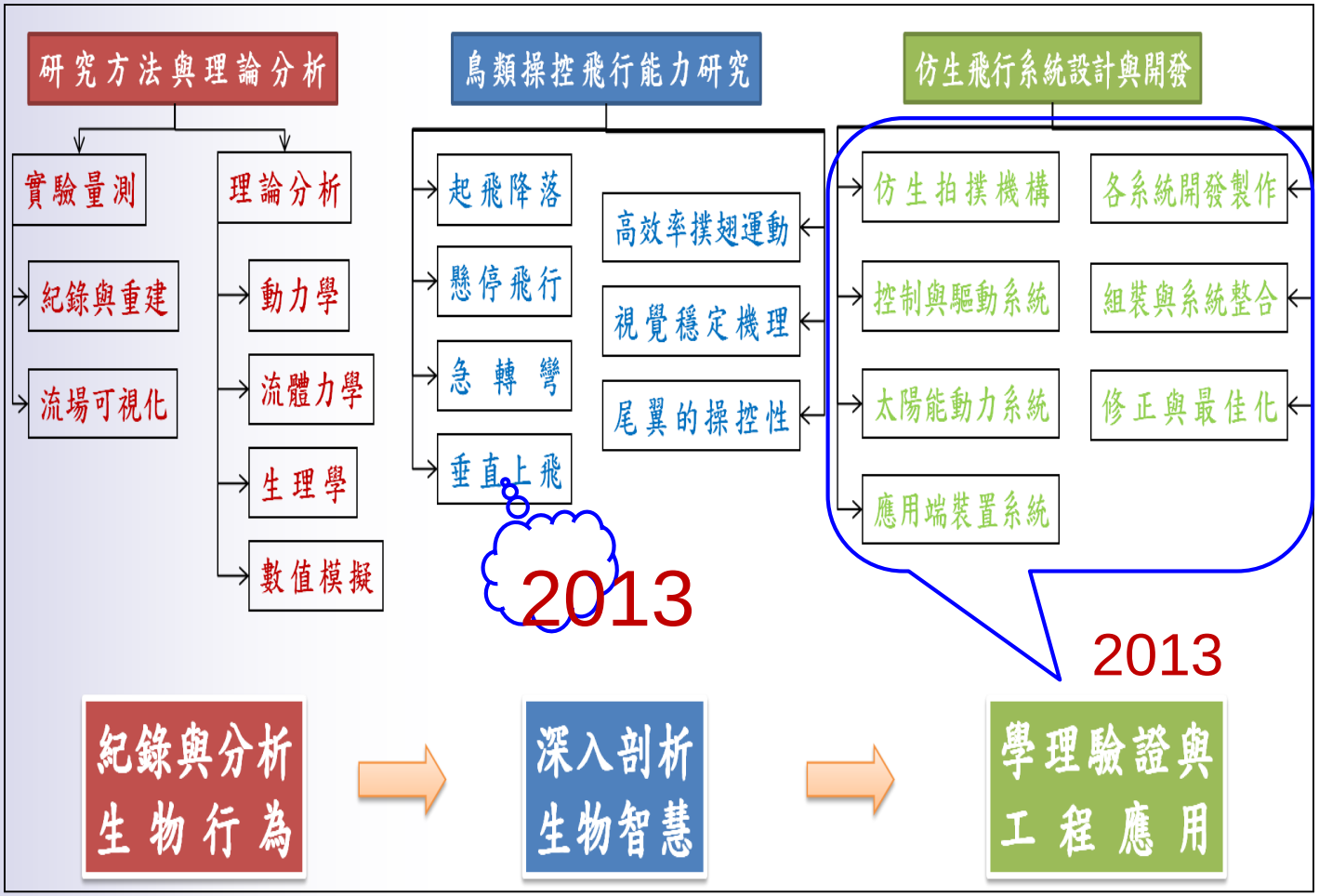
楊鏡堂, 航太學門計畫

NSC 100-2221-E-002-135 -MY3

**wisdom of creatures**

從生物智慧的觀點，可運用於具前瞻性的高雷諾數懸停撲翼式飛行器之設計，有效提升其飛行穩定性與操控性。

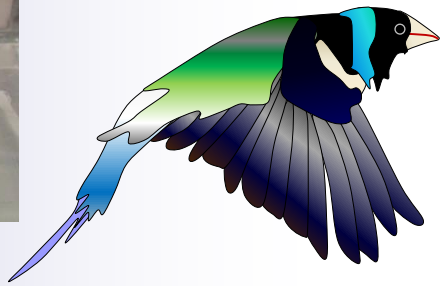
# Objectives of the Biomimetics Project



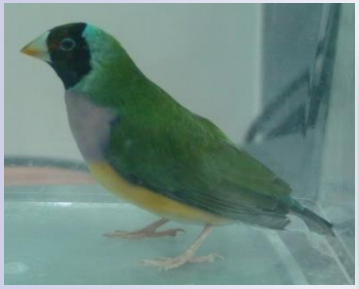
# Experimental Species

***Observation, Learning, Imitation, Inspiration → Creation***

Japanese White-eye



Damselfly (豆娘;中華珈璁), *Psolodesmus mandarinus*
*Weight: 15-20 g; Wing span: 8-12 cm*
*Flapping frequency: 1.5-2.0 Hz*



Golden Finch (F)

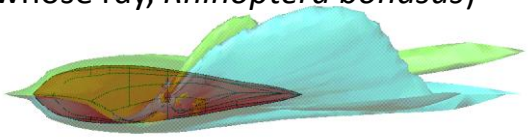
http://hrqpdzhrq.blog.163.com/blog/static/90982170200881010422963/

Tinfoil barbs (泰國鯽), *Barbonymus schwanenfeldii*

Boeing 797

Golden Finch (M)

batoid fish 紅魚
(cownose ray, *Rhinoptera bonasus*)



Indian leaf butterfly (枯葉蝶), *Kallima inachus*

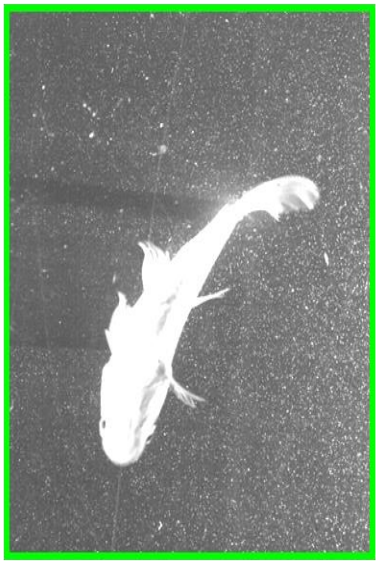
- ✓ *Weight: 0.4 g; Wing span: 6.5 cm*
- ✓ *Flapping frequency: 10-12 Hz*

# Biomimetic research in BEAM Lab.

楊鏡堂教授, 台大機械系

模仿並創新!

血鸚鵡魚



朱文錦魚

長腳潔淨蝦

綠繡眼

蜻蜓

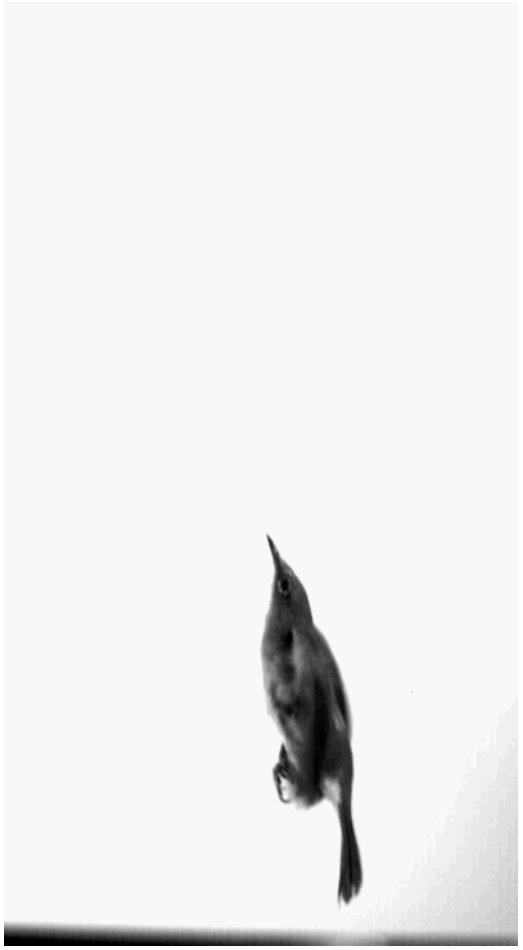
鳳蝶

紋白蝶

# *Bird's flapping flight* … 綠繡眼飛行秀

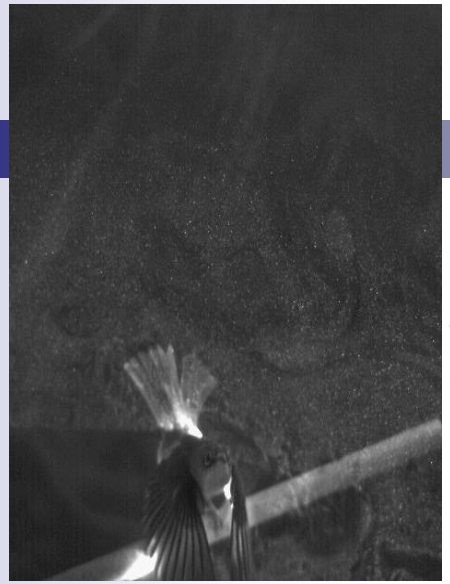
楊鏡堂, 台大機械, 2011

Hovering 懸停飛行

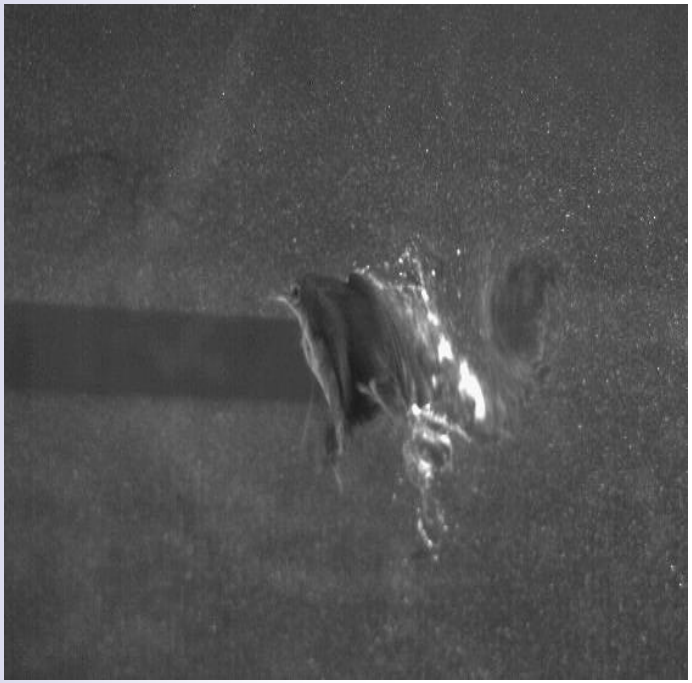


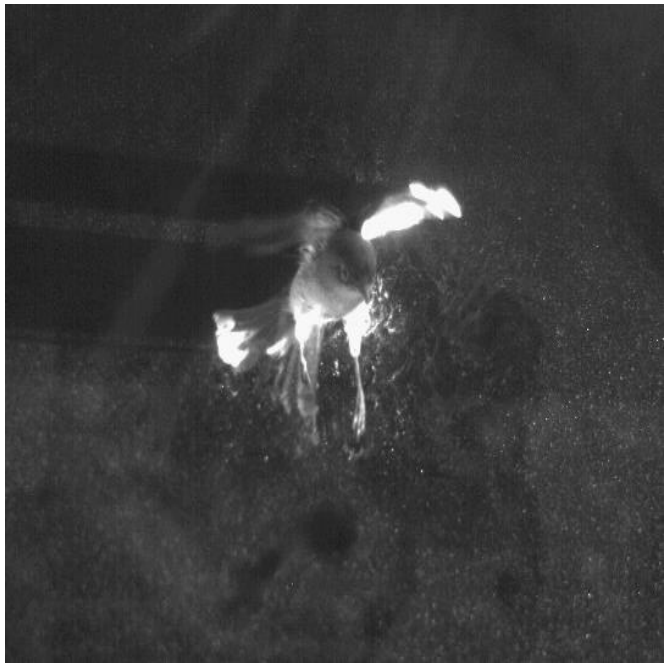
Ascending 爬升飛行

拍攝於 BEAM Lab.



# 鳥類拍撲飛行流場可視化技術



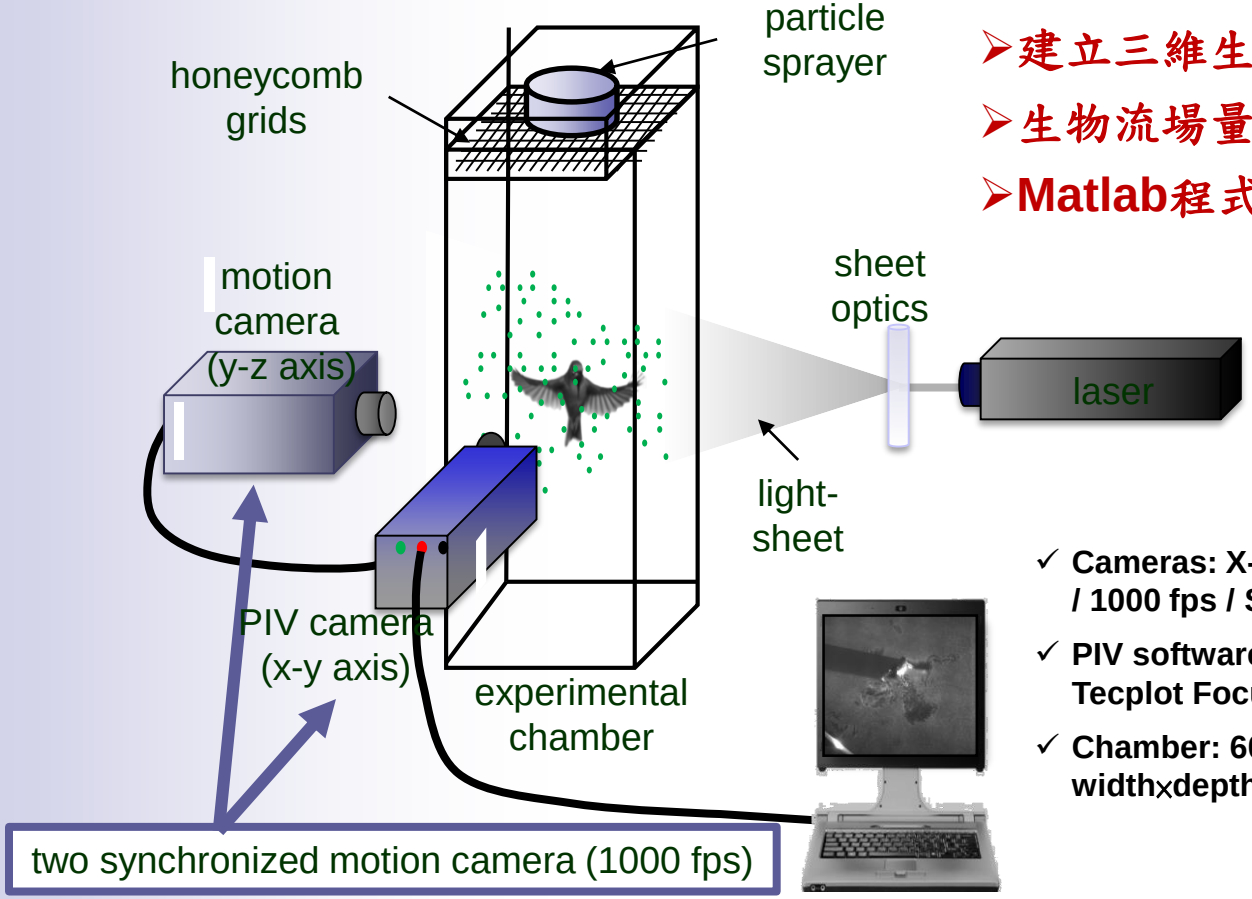


NTU, BEAM Lab.

# 粒子影像測速儀(PIV)

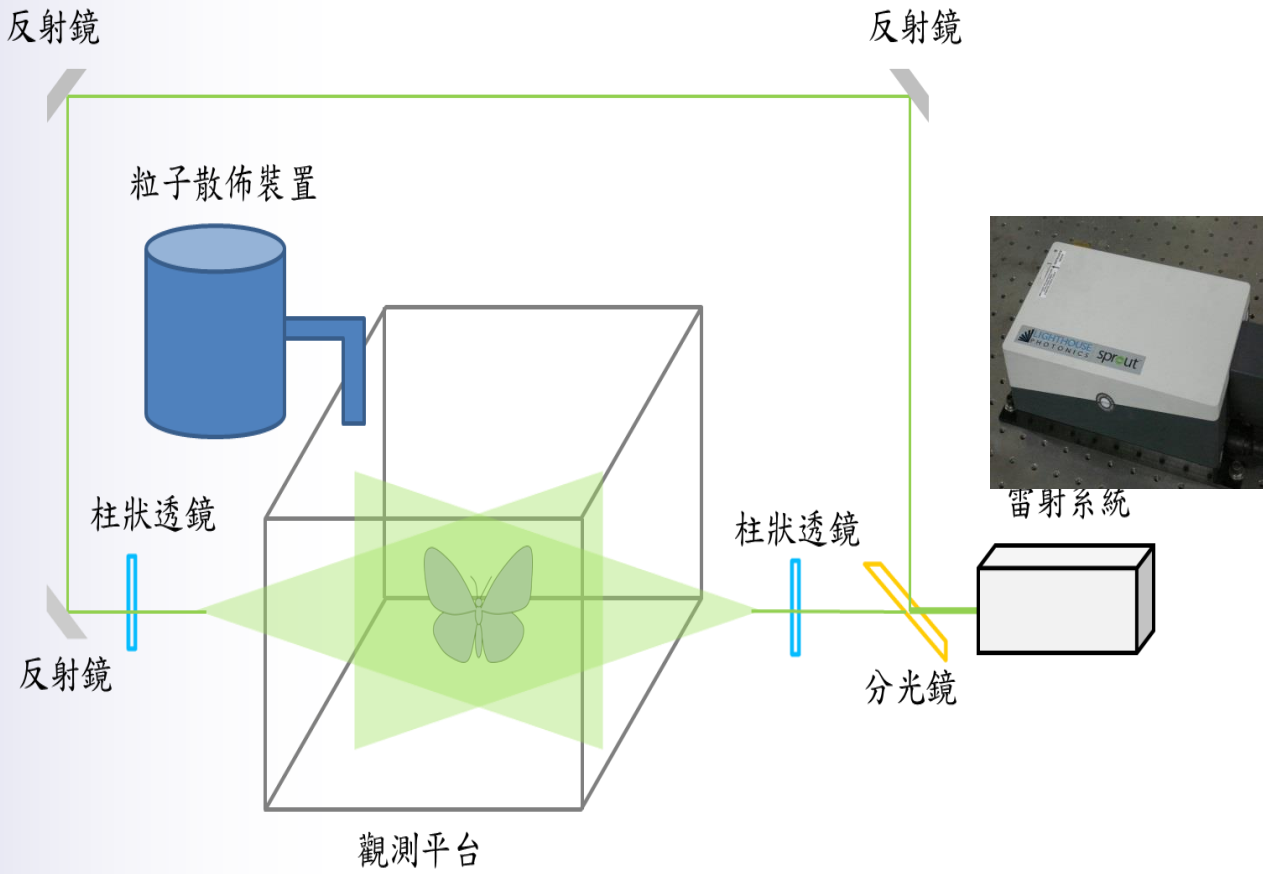
章聿珩碩士論文, 台大機械, 2011

- 高速攝影機拍攝
- 建立三維生物運動量測與分析系統
- 生物流場量測與計算
- Matlab程式撰寫計算升力

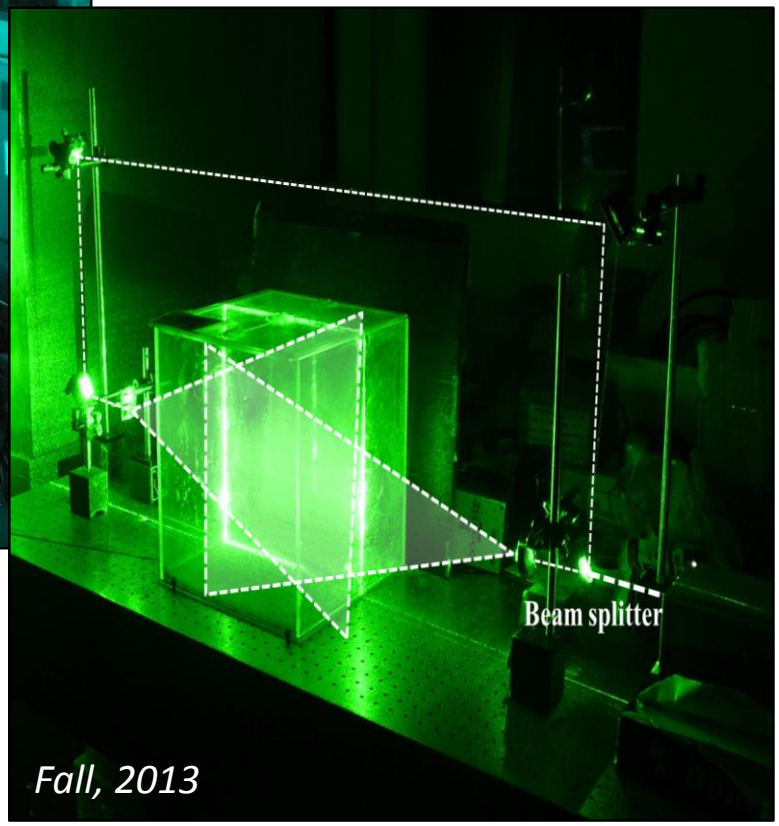



- ✓ **Cameras: X-Stream TM Vision 5, IDT Inc. / 1000 fps / Synchronized & Ortoalgonal**
- ✓ **PIV software: Insight 3G (TSI Inc.) and Tecplot Focus 2008**
- ✓ **Chamber: 60 cm × 60 cm × 120 cm, width×depth×height**

# 空氣中觀測實驗系統示意圖



# 蝴蝶/豆娘 飛行之實驗測試圖

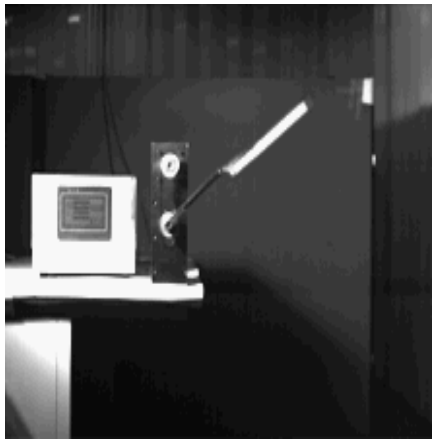



# 實驗影片 in BEAM Lab.

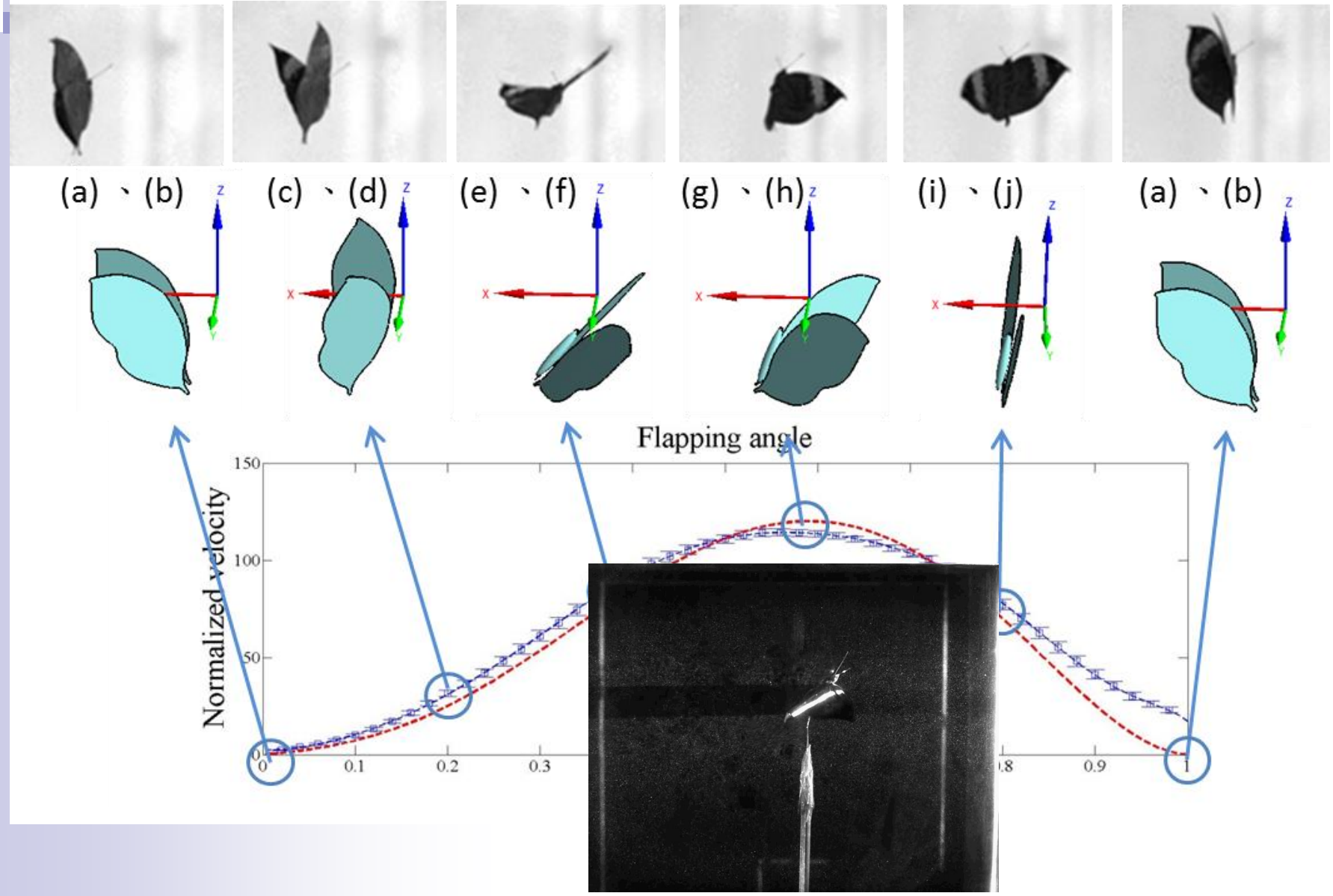
# Flapping-wing model

楊鏡堂, 台大機械, 2011

章聿珩碩士論文, 台大機械, 2011

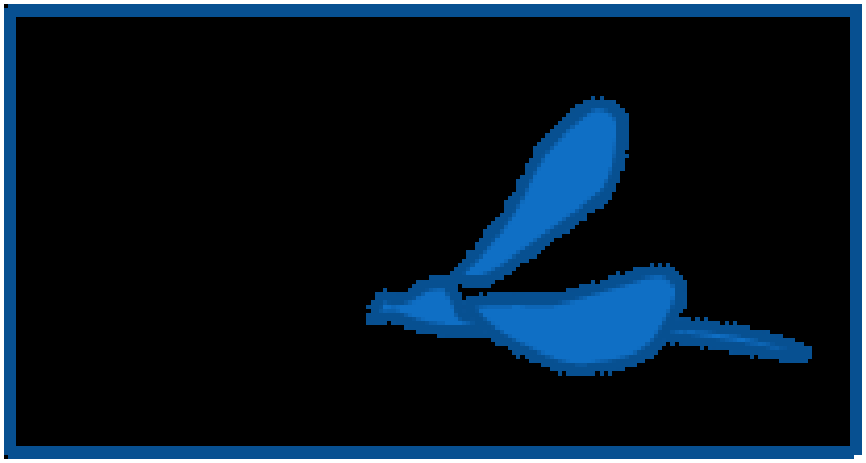
# Real Motion and Simulation



# Motion Analysis

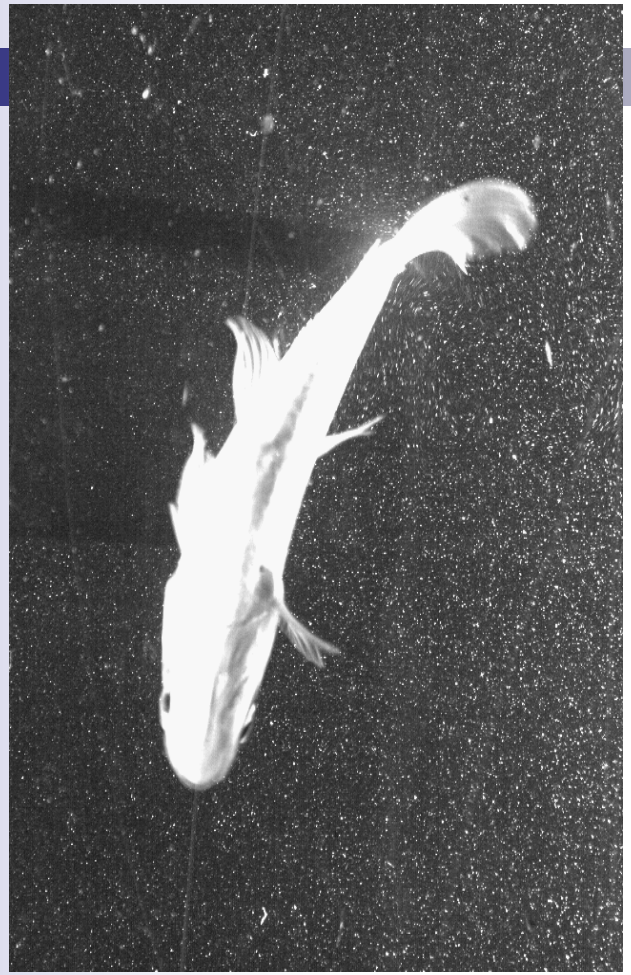
Forward Fly
(Re=2900)

Sharp turn with body rotation (Re=2200)



**Sharp turn without body rotation (Re=1000)**

# 生物運動力學



***Swimming fish***

(Crucian carp, 鯽魚)

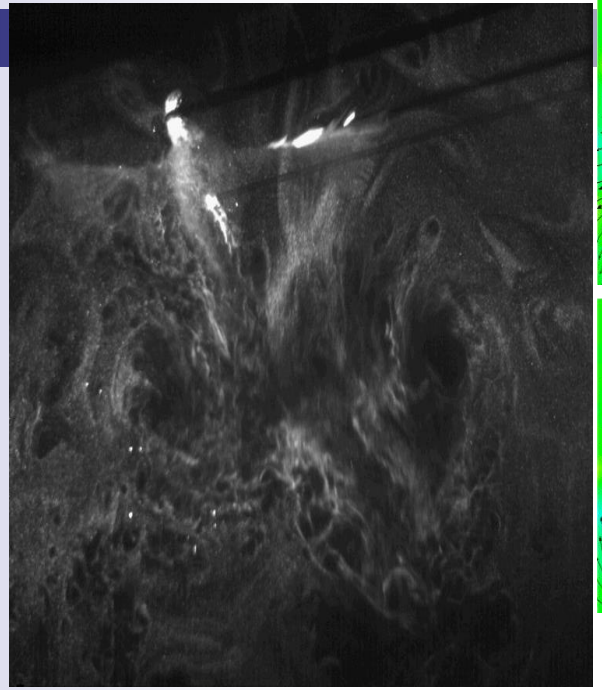
***Hovering bird***

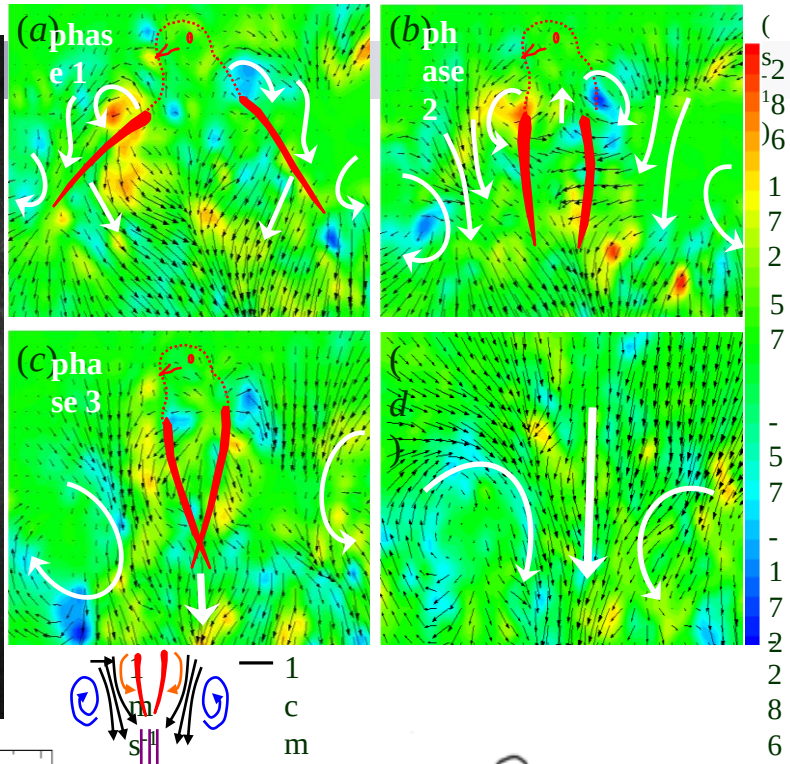
(Japanese white-eye, 綠繡眼)

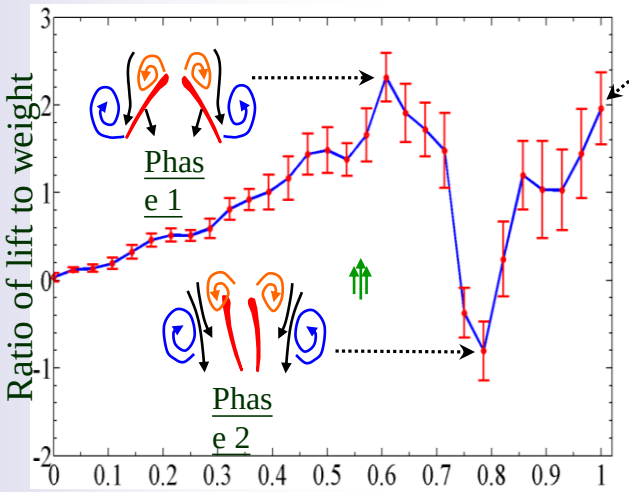
**Flow Visualization**

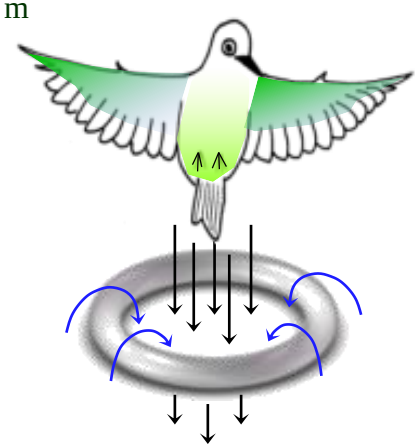
# Flowfield and Lift Generated from Flapping Wings

楊鏡堂,
台大機械, 2011



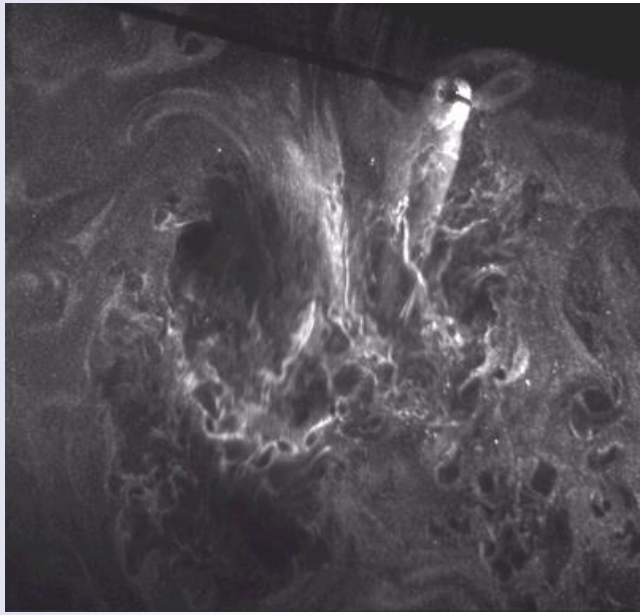


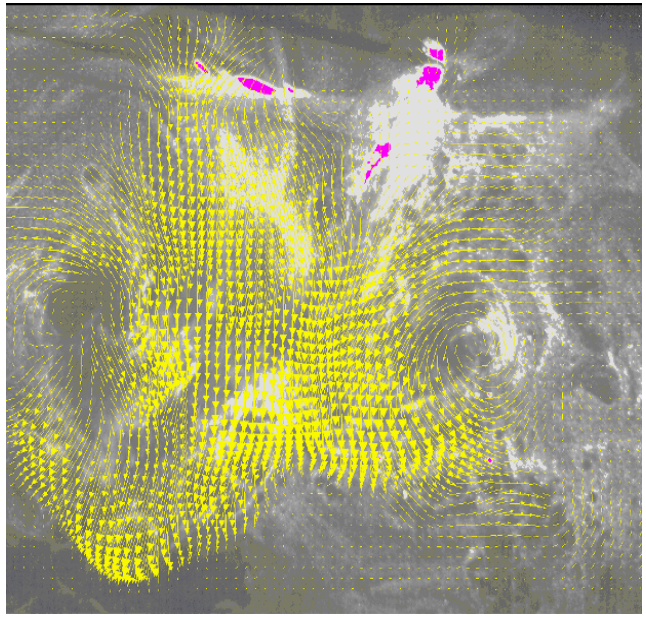



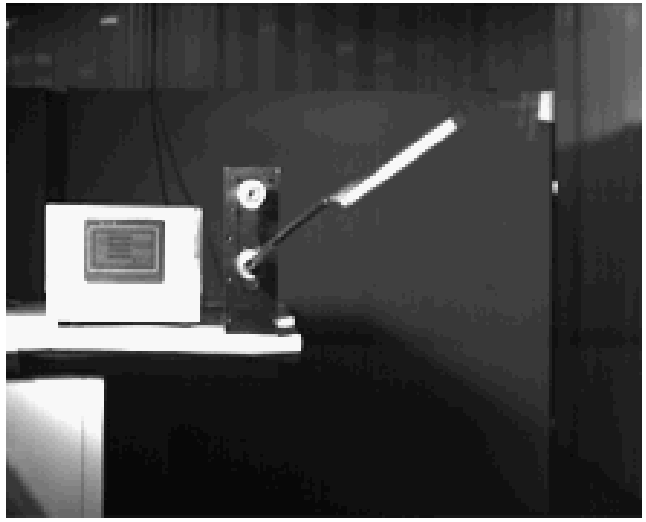



尾流渦環結構

# 小型鳥類懸停飛行之生物實驗與拍撲機構模擬





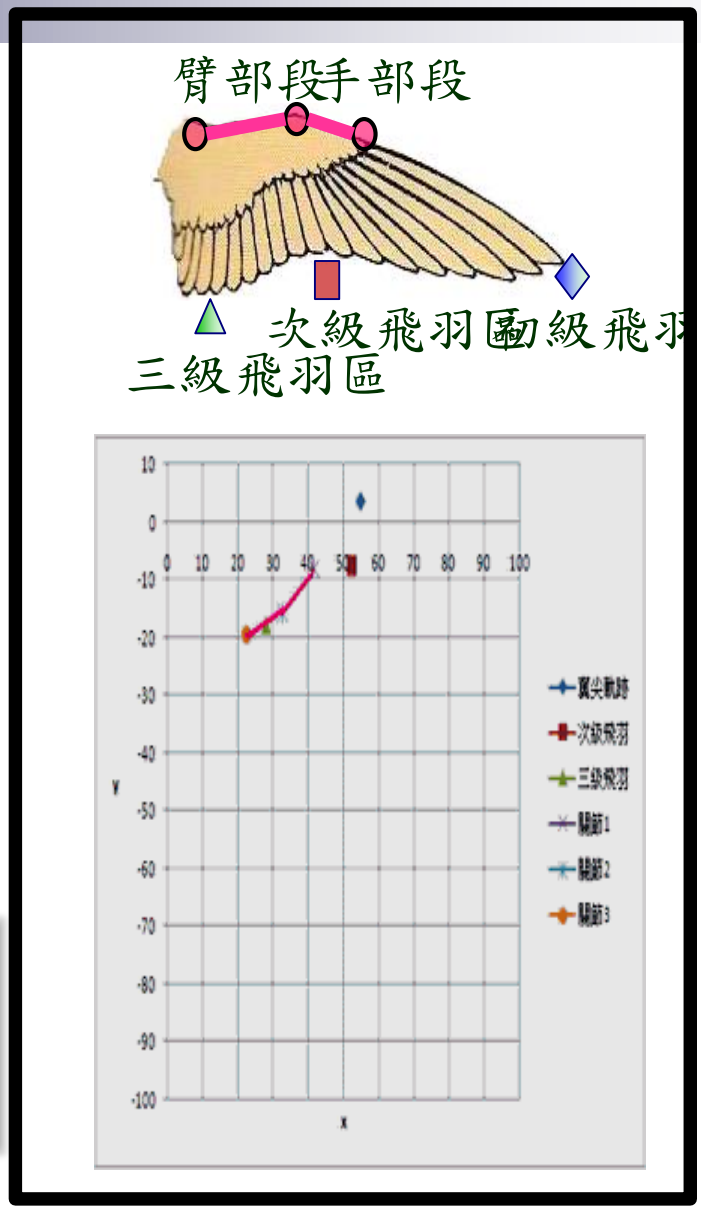


# Wing Motion

楊鏡堂, 台大機械, 2011

綠繡眼懸停

飛行↓

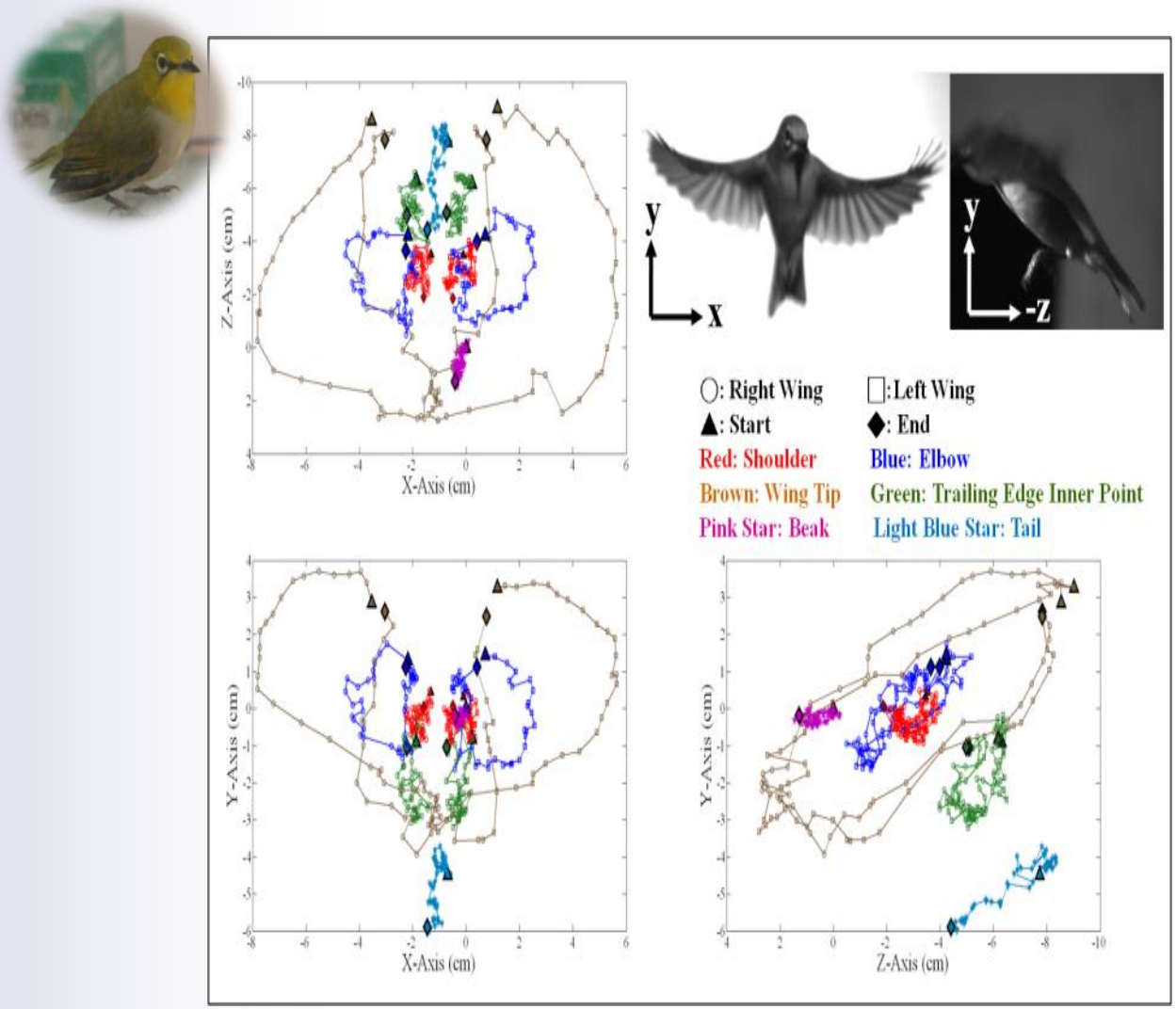



追蹤翼面軌跡作為可摺曲翼展機構設計參考→

# 3D運動學分析結果

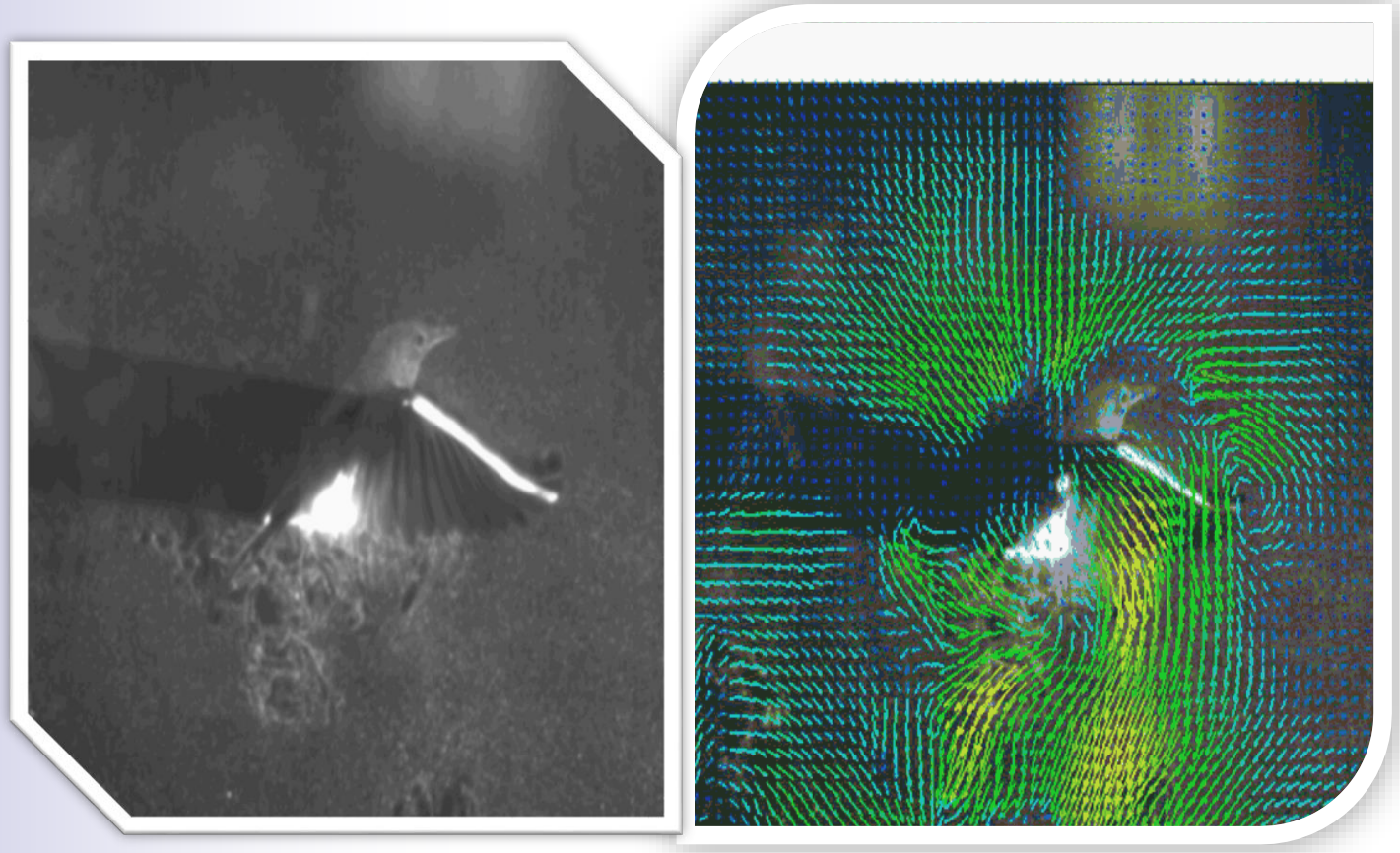
楊鏡堂, 台大機械, 2011

章聿珩碩士論文, 台大機械, 2011

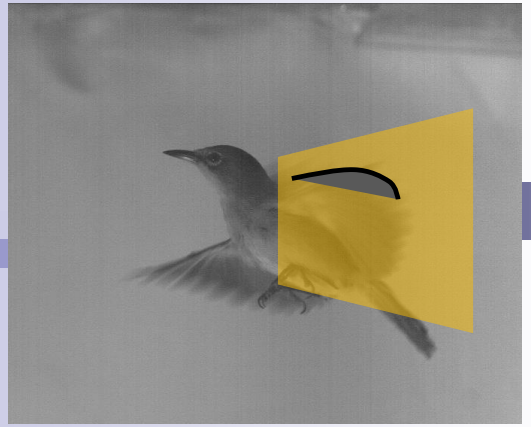


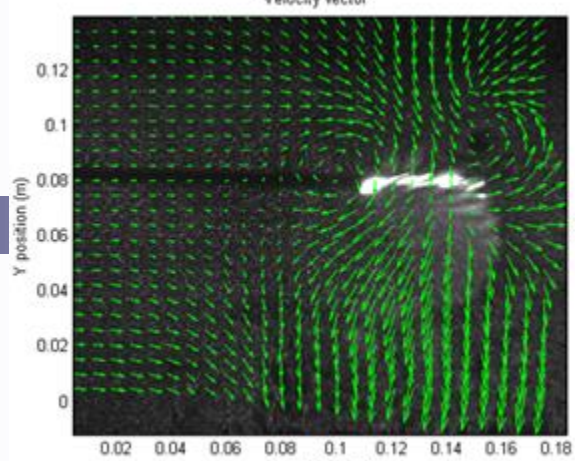
# PIV流場觀測

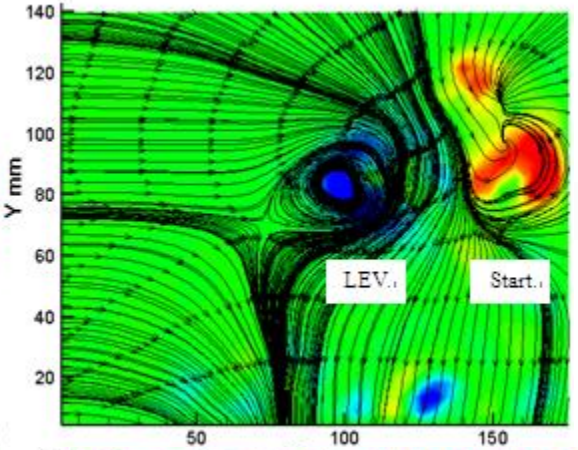
蘇健元論文, 台大機械博士, 2013

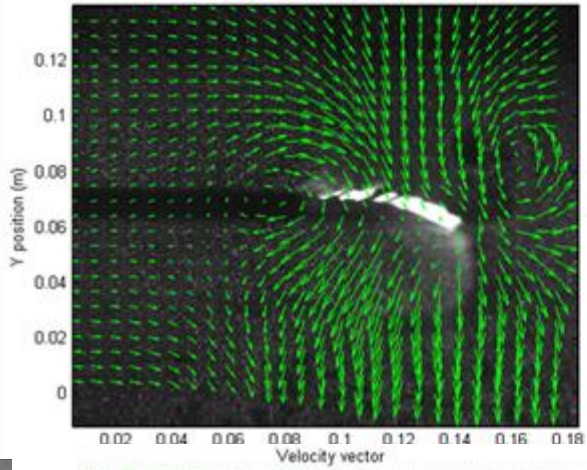


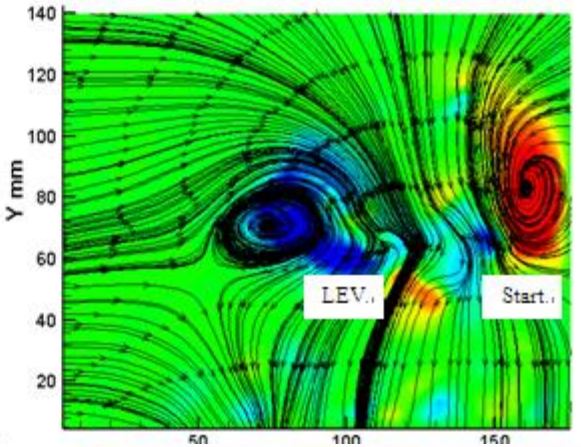
*Particle Image Velocimetry (PIV)*

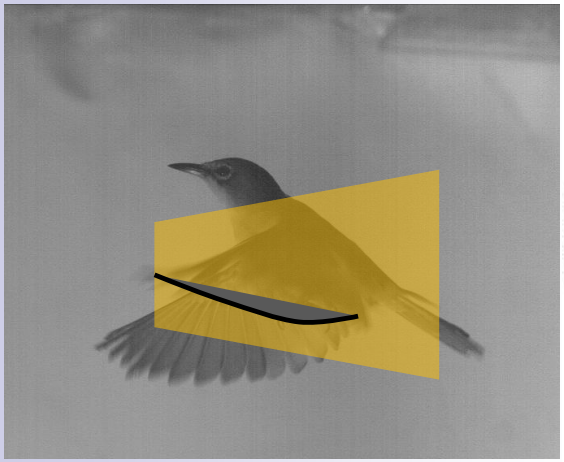


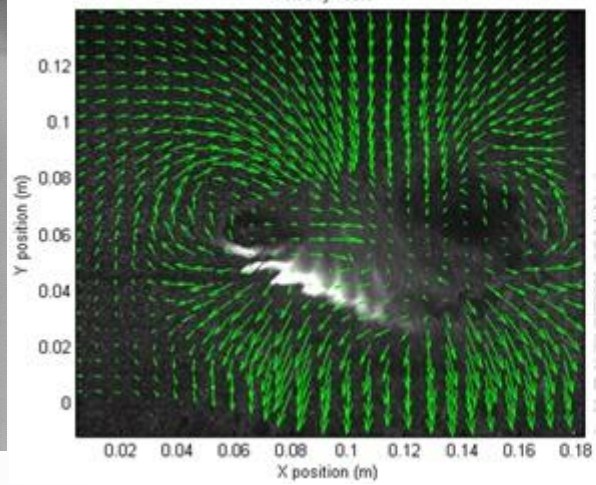

Y position (m)
0.12
0.1
0.08
0.06
0.04
0.02
0
0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18

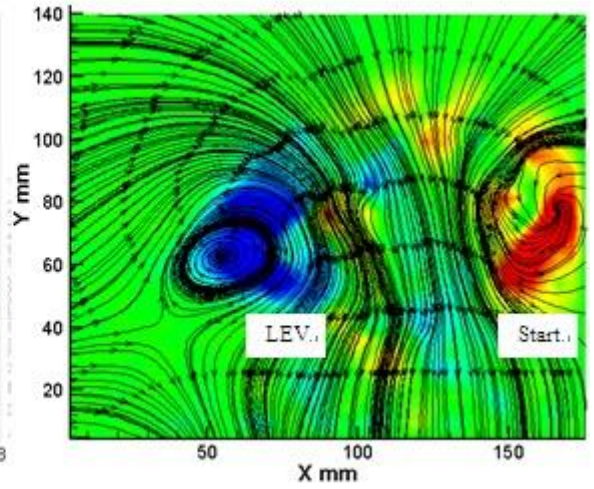

Y mm
140
120
100
80
60
40
20
50 100 150
LEV.
Start.


Y position (m)
0.12
0.1
0.08
0.06
0.04
0.02
0
0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18
Velocity vector

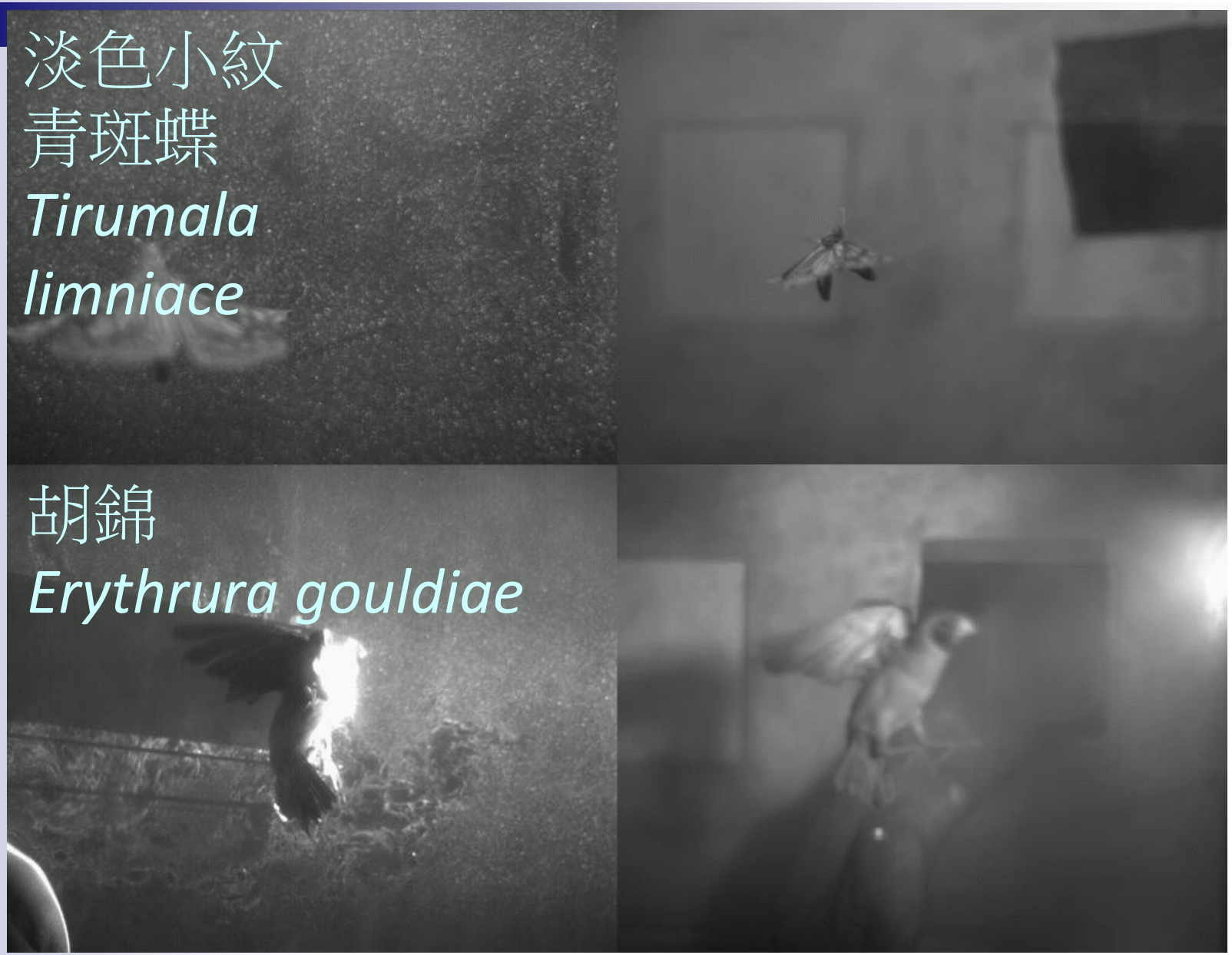

Y mm
140
120
100
80
60
40
20
50 100 150
LEV.
Start.




Y position (m)
0.12
0.1
0.08
0.06
0.04
0.02
0
0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18
X position (m)


Y mm
140
120
100
80
60
40
20
50 100 150
X mm
LEV.
Start.

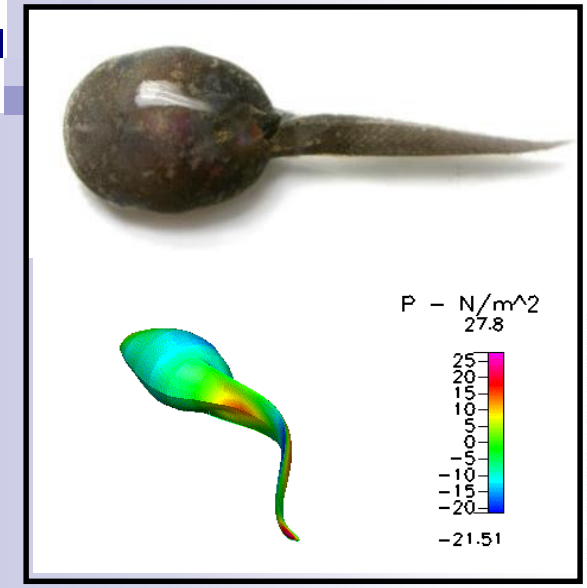
# Synchronized PIV & Motion Analysis



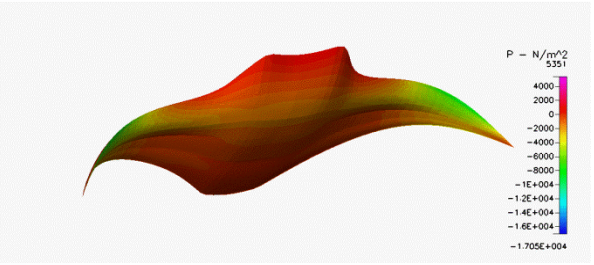
# Computational Fluid Dynamics

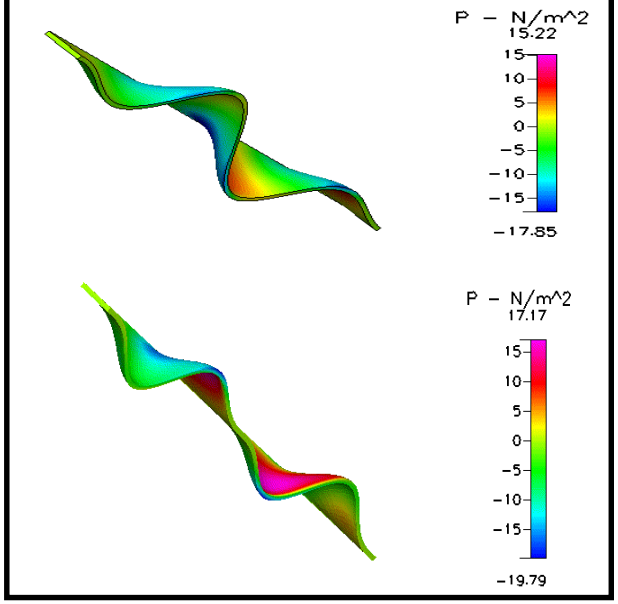
## *Animal Locomotion*

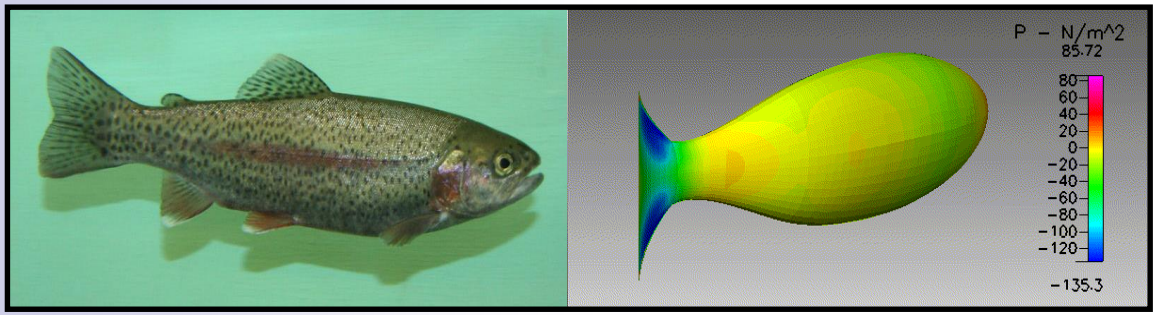
# Fish Swimming and CFD Simulation

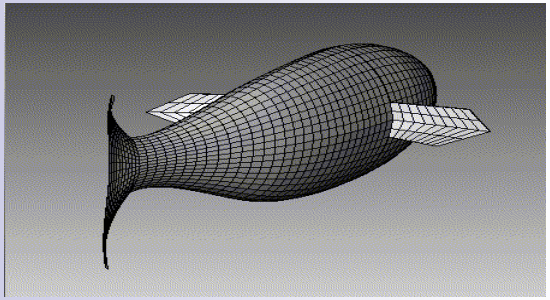


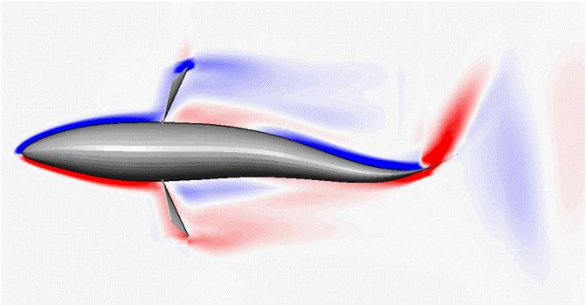


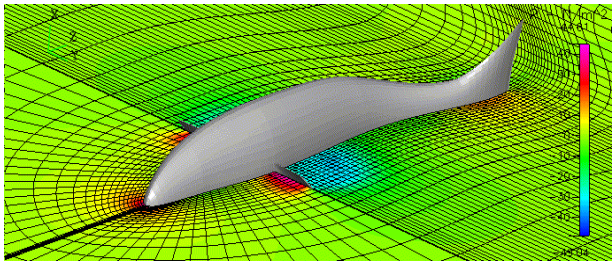


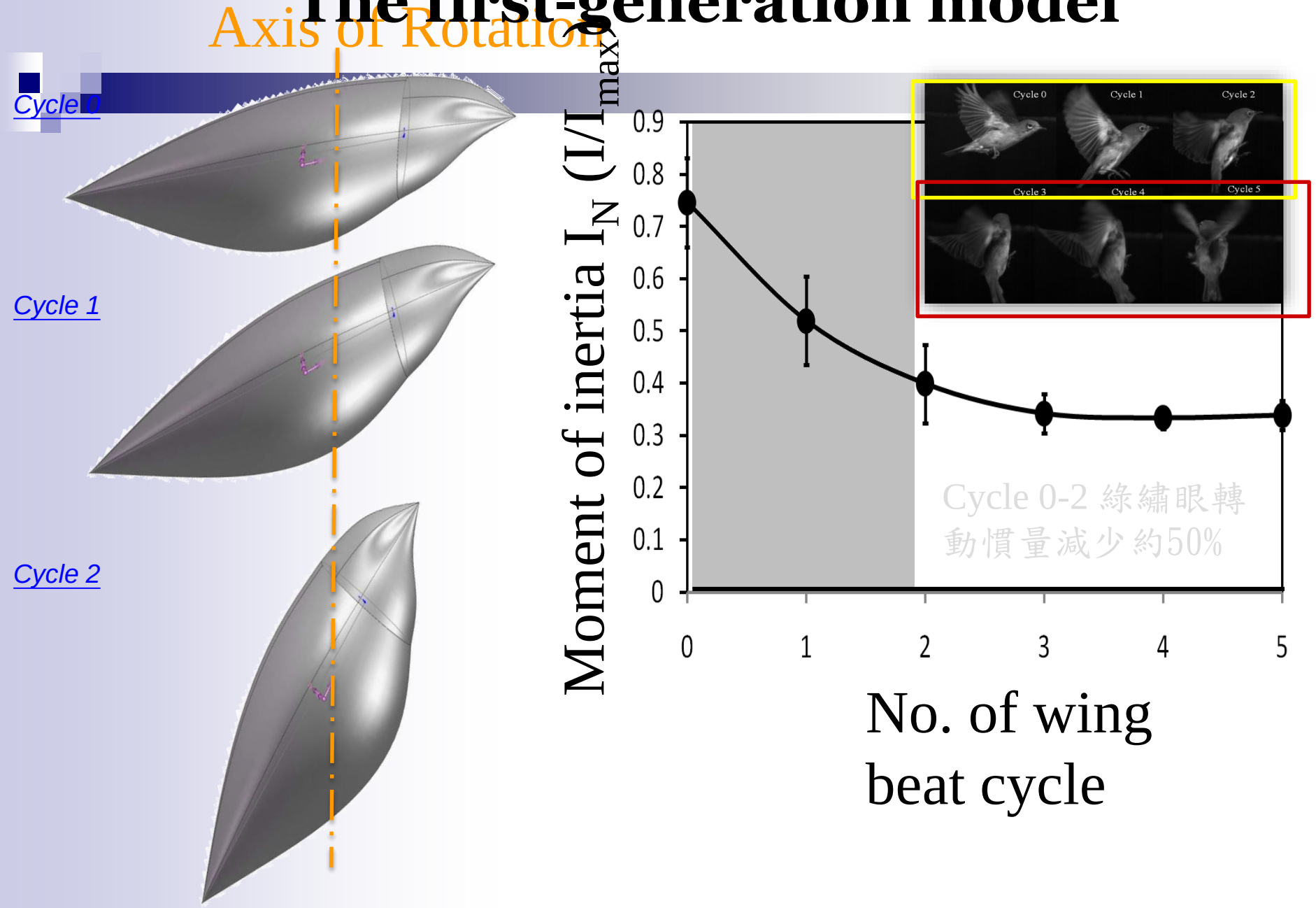





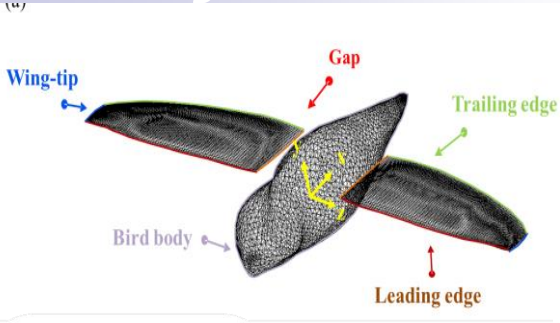


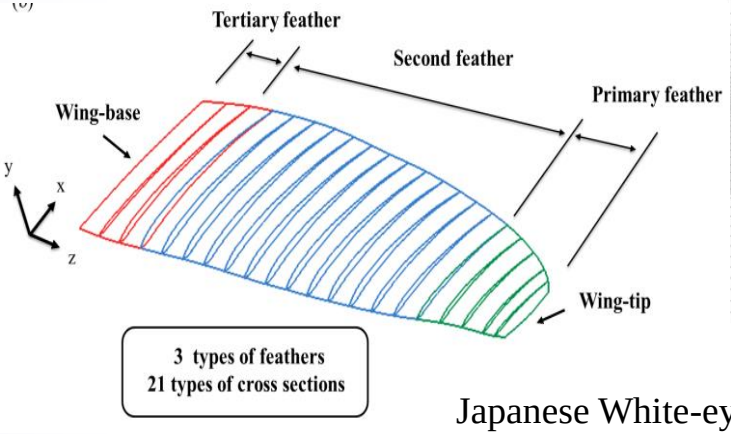
# The first-generation model

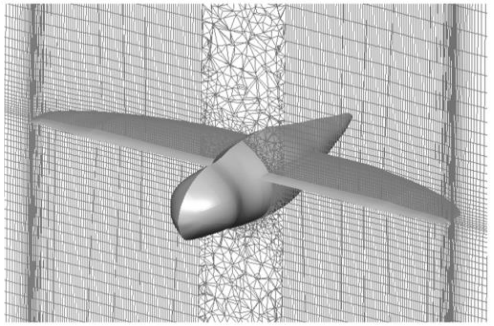


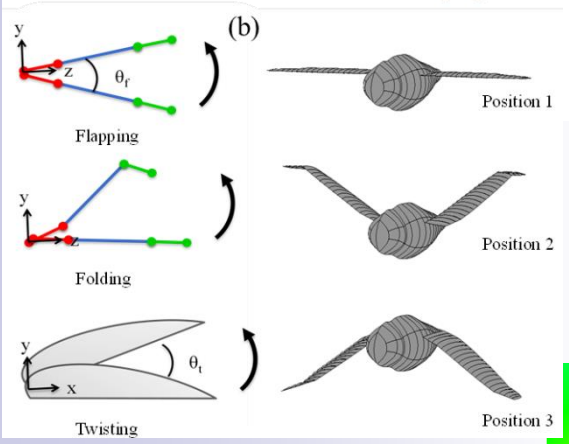
# A numerical investigation on the ground effect of a flapping-flying bird

## Physics of Fluids, 2013

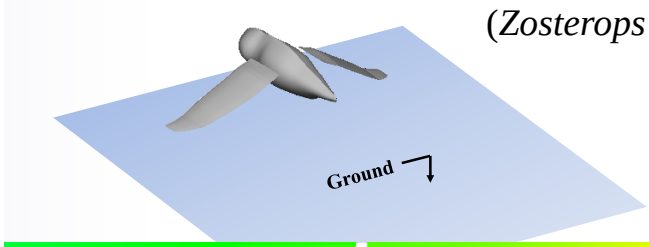


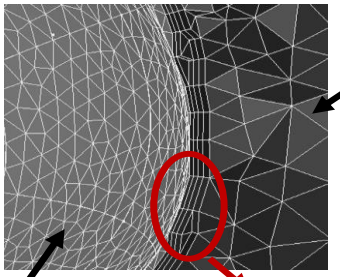



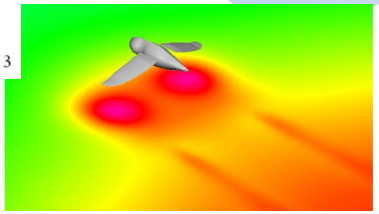



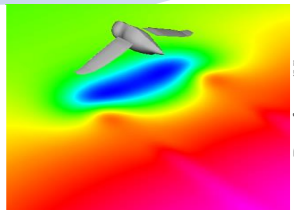



Japanese White-eye
(*Zosterops japonicus*)

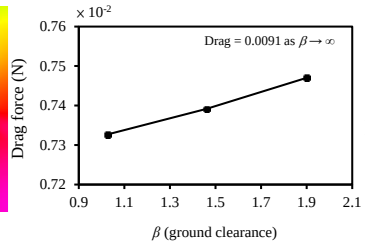


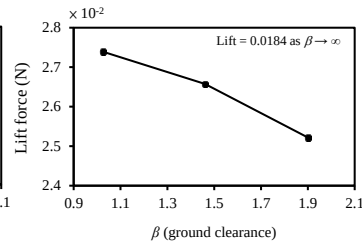



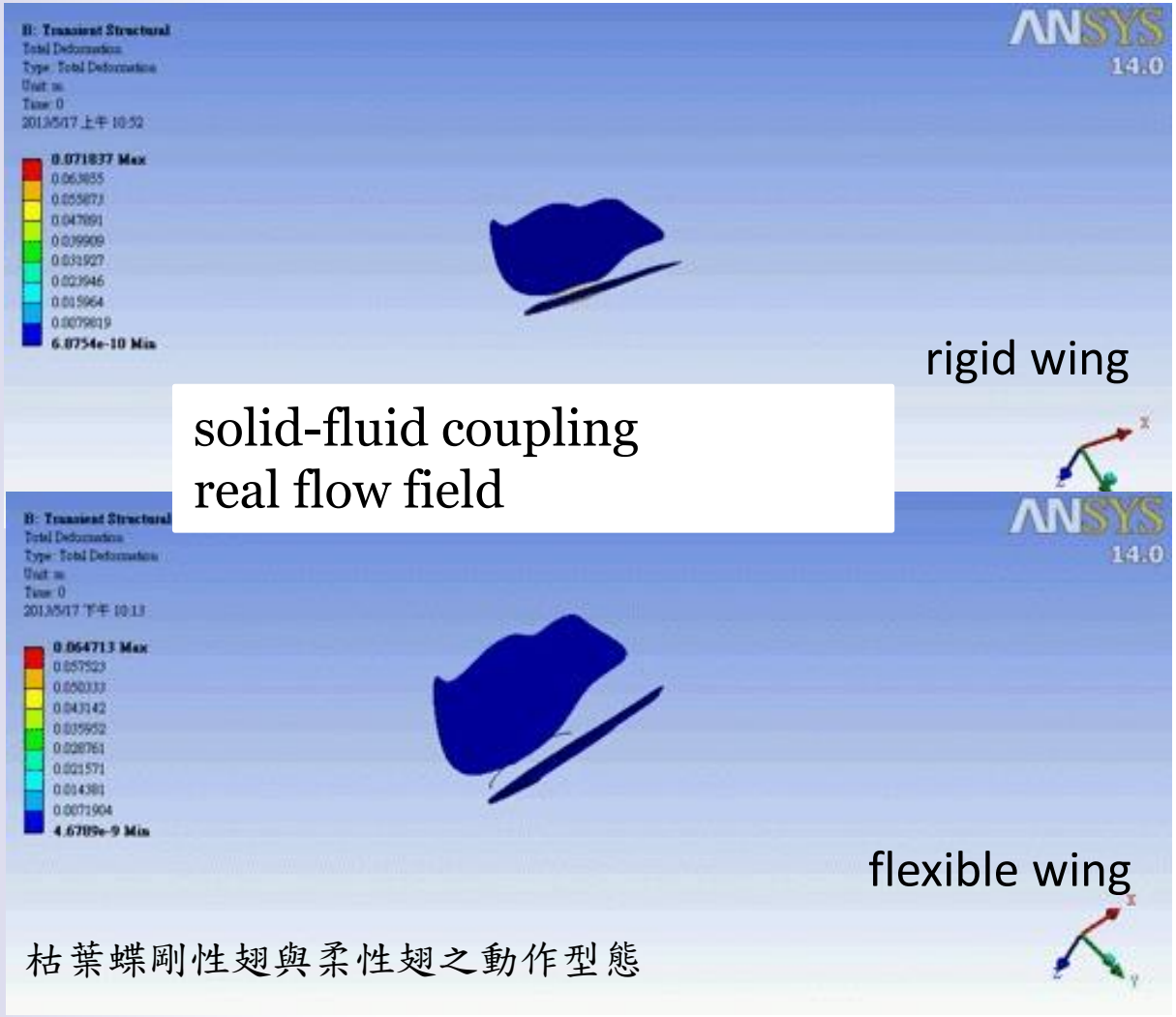


(a) downstroke (b) upstroke



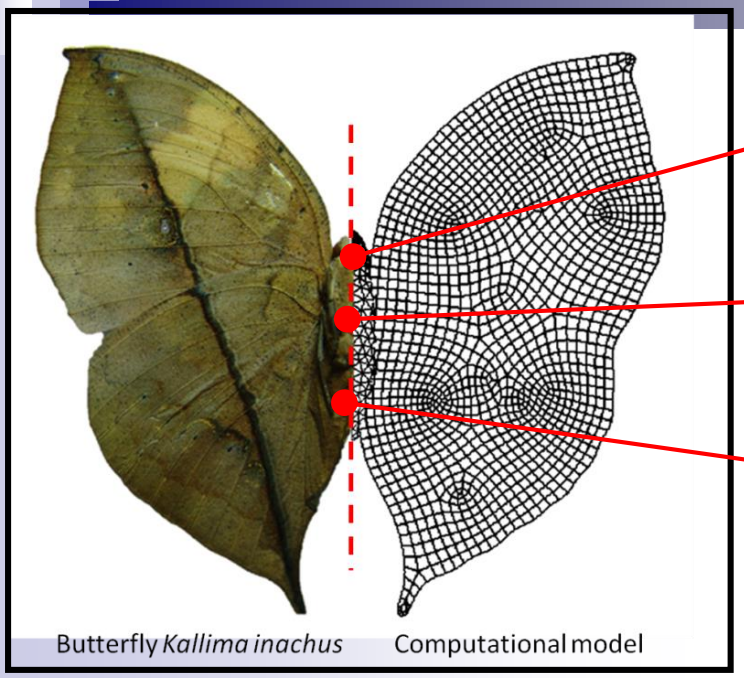




The flight of a small bird under the influence of the ground effect is numerically investigated with a complete three-dimensional model including the bird's body and wings.



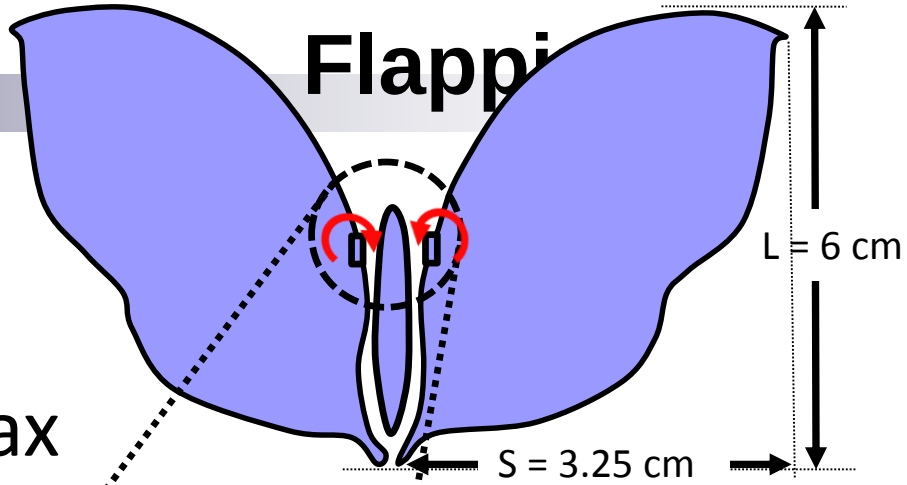

(Fei's MS Thesis, June, 2014)

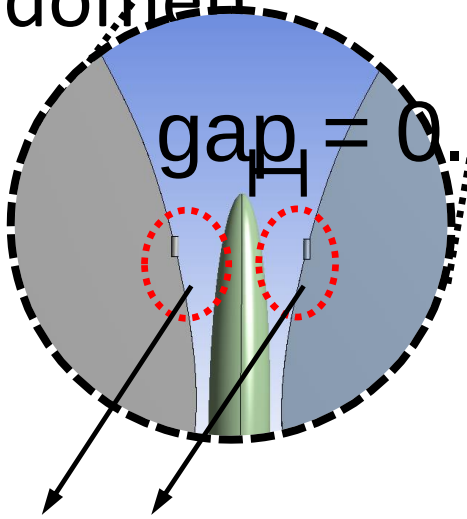
# Structure Model



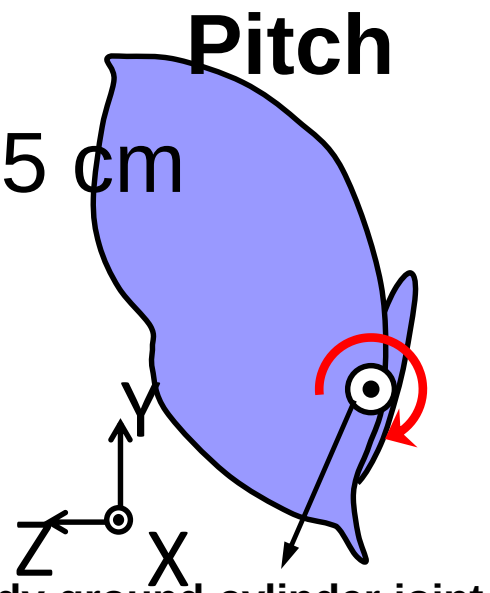

In this case, head thorax and abdomen are considered as a shuttle shape body.

- ✓ **Young modulus = $2\times10^{12}$ Pa**
- ✓ **Density = 1200 kg/m$^3$**
- ✓ **Total mass = 0.395 kg**
- ✓ **Grid number = 14,000**




**Body-wing cylinder joint (1-DOF)**




**Body-ground cylinder joint (1-DOF)**

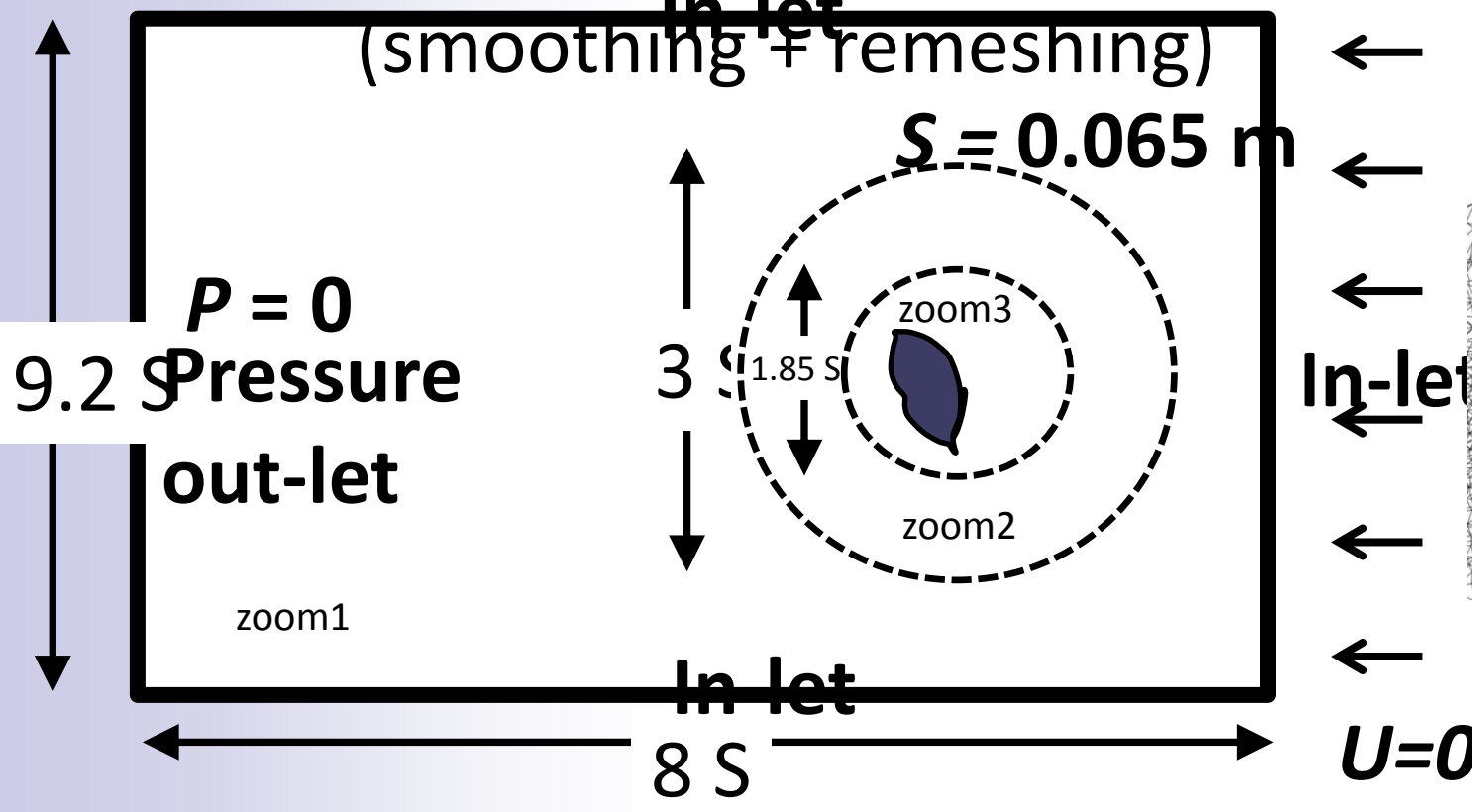
# Boundary Conditions

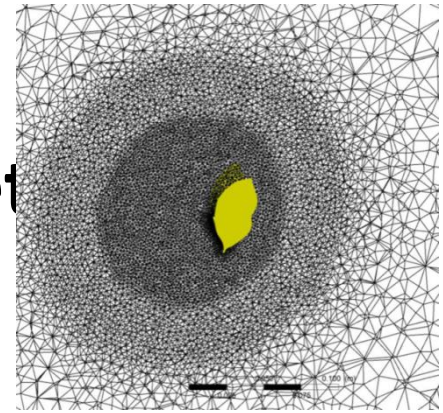
zoom1: stationary zoom

zoom2: small-mesh zoom

zoom3: dynamic-mesh zoom (smoothing + remeshing)

$$fluid : air$$
$$\rho : 1.225\ kg\ m^{-3}$$
$$\mu : 1.79\times10^{-5}\ kg\ m^{-1}s^{-1}$$



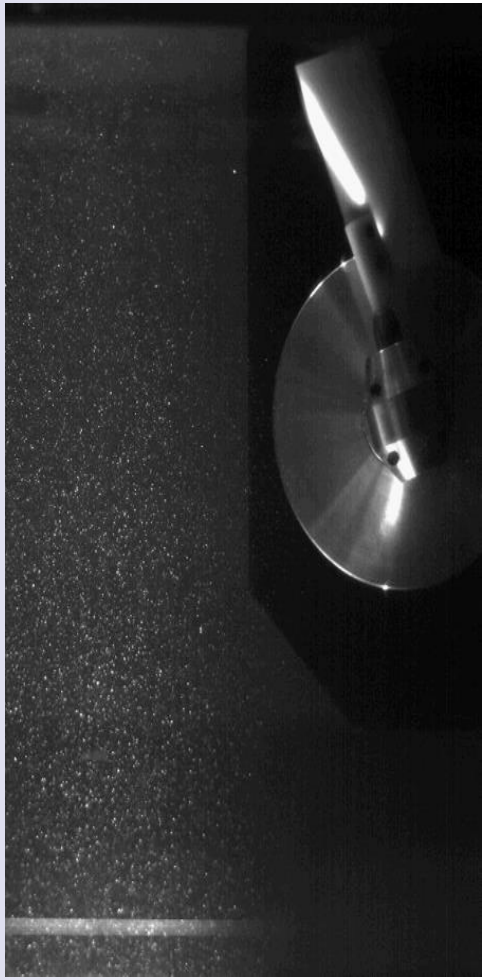
Grid number: 1800000

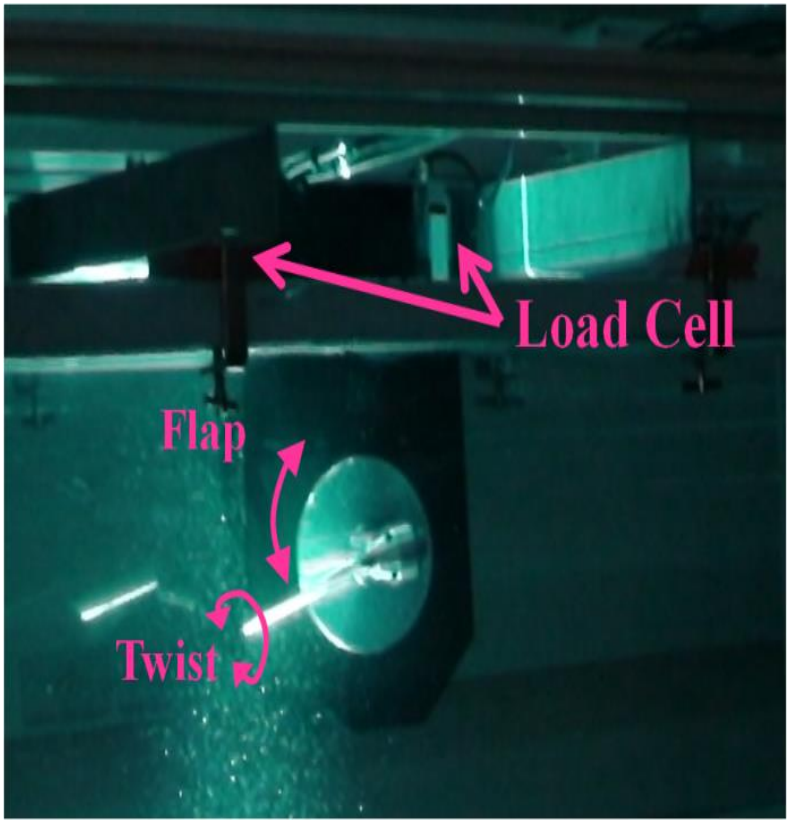
Time step: 0.00025 s

(250 steps per period)

# 仿生物智慧拍撲機構設計

章聿珩碩士論文, 台大機械, 2011

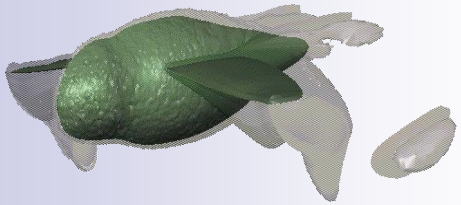




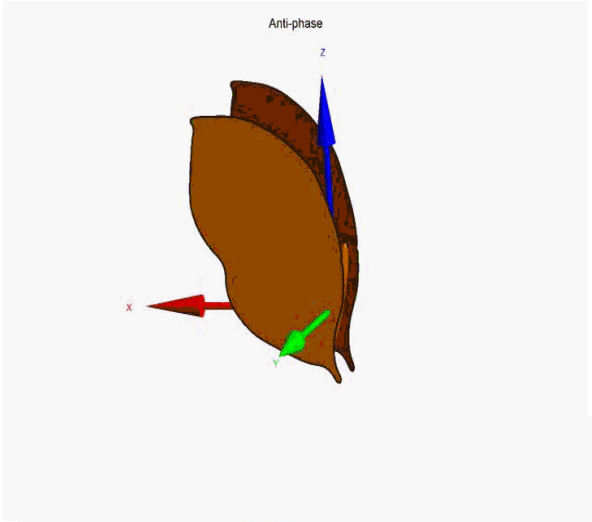

模仿鳥類的flap與twist動作

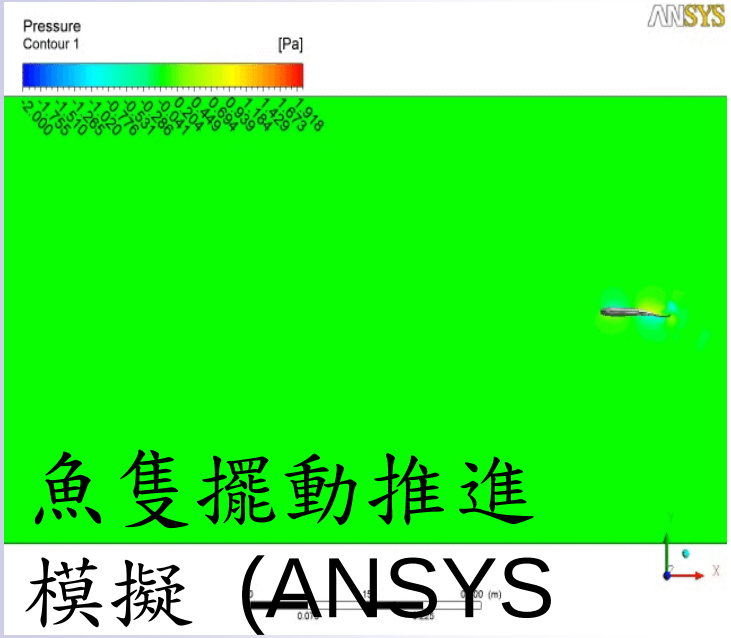
# 仿生數值模擬 in BEAM Lab.

利用CFD商業軟體CFD-ACE+ 和 ANSYS 模擬生物運動時的流場現象:



鳥類拍翅



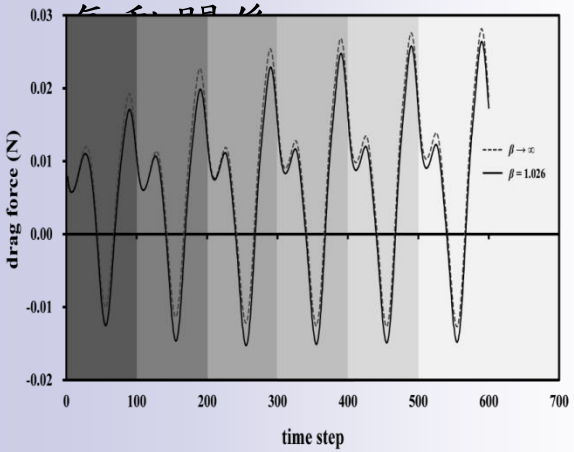

魚隻擺動推進模擬 (ANSYS

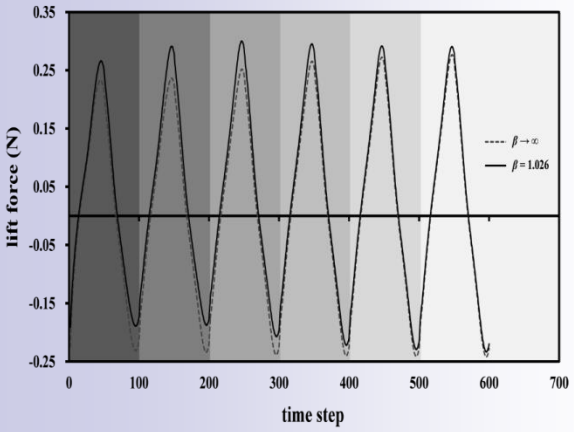
蝴蝶拍翅模擬 (ANSYS

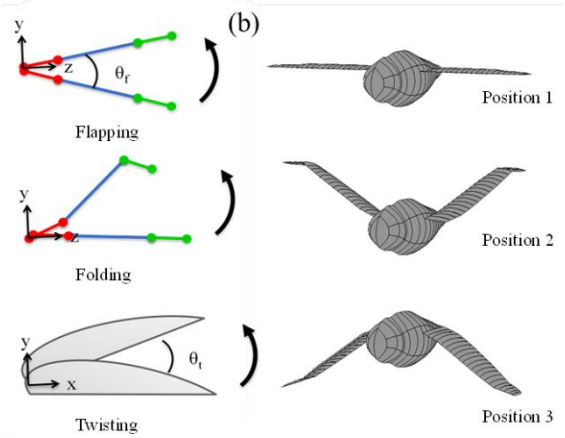
# 鳥類拍翅模擬 (CFD-ACE+)

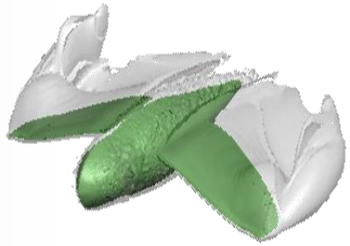
利用CFD-ACE+的動態網格模擬

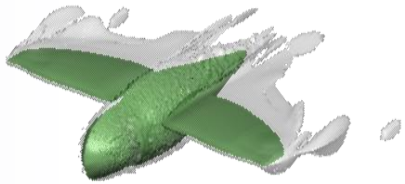
鳥類拍撲翼與翼地效應之

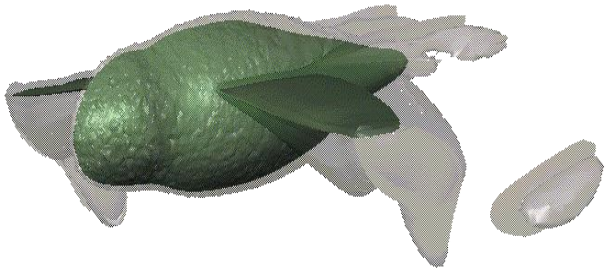


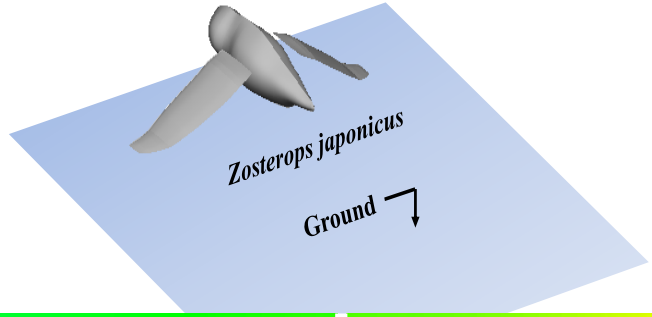



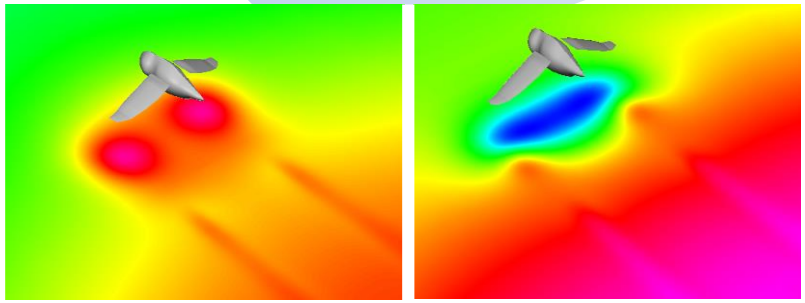







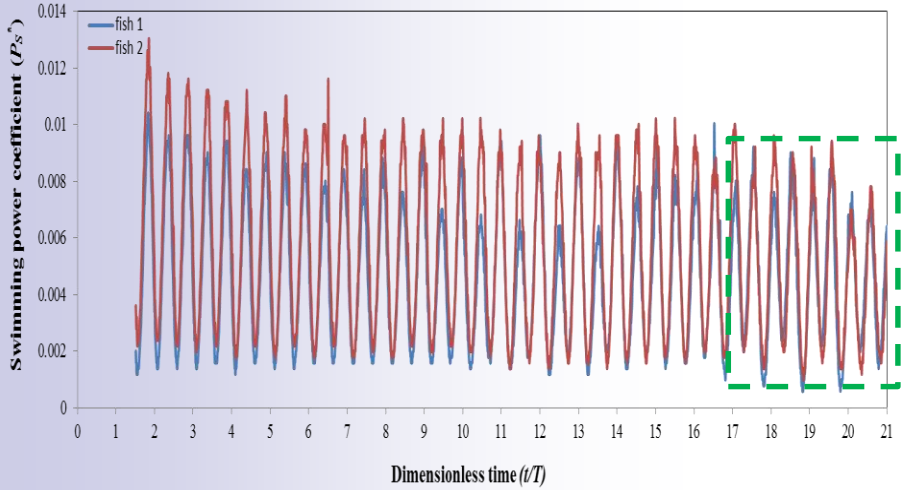


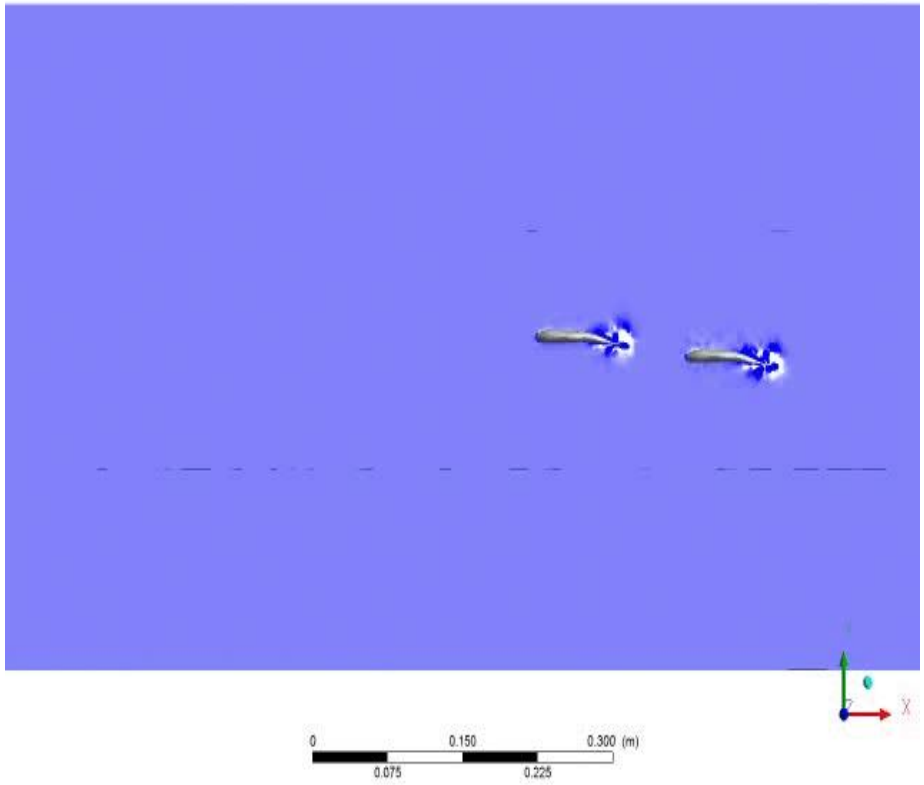



(a) downstroke (b) upstroke

# 魚隻定頻擺動的數值模擬

利用ANSYS FLUENT的用戶自定義函數(UDF)搭配動態網格來模擬魚隻在水中定頻擺動的運動。




此刻下游魚隻追趕至並排且頭部漸超越上游魚隻的位置

# 鳥類視覺防震系統

# Chicken Head Steadicam

http://www.youtube.com/watch?v=m8sNHd0U7yw

頭部包含許多重要器官，生物運動時會刻意穩定其頭部

頸部結構類似汽車之懸吊系統 ！

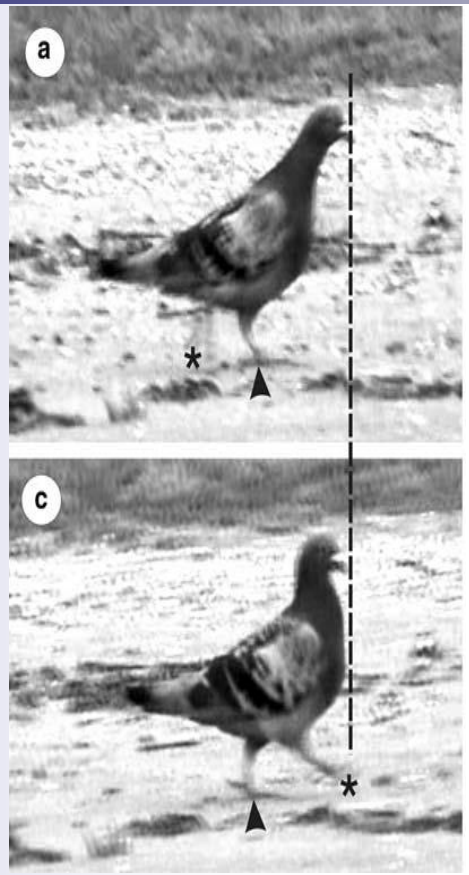
# Bird Head Steadicam

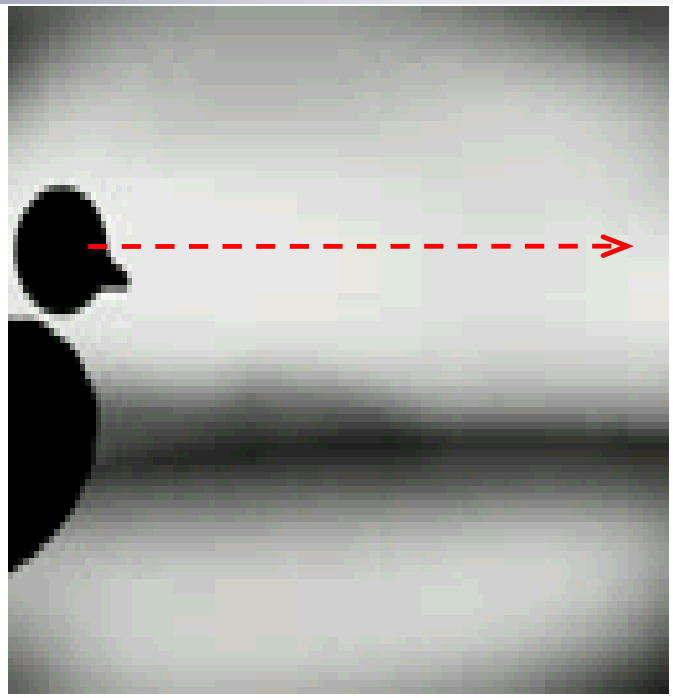
http://www.youtube.com/watch?v=8NXclg93-V8&feature=mfu_in_order&list=UL

此一生物機制可應用於行車記錄器或是防手震相機

# 鴿子行走

# 鴿子行走時的頭部穩定



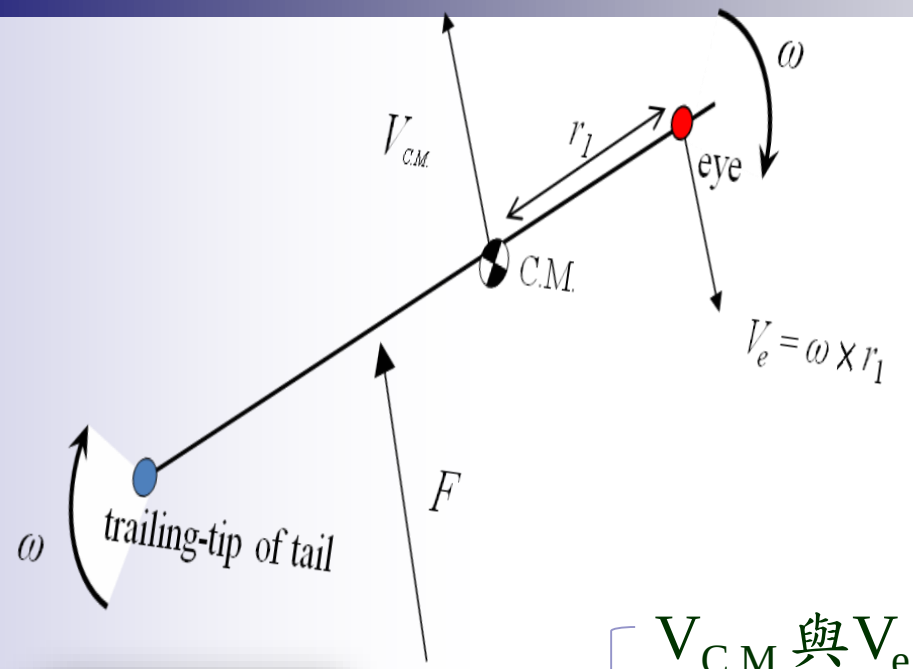



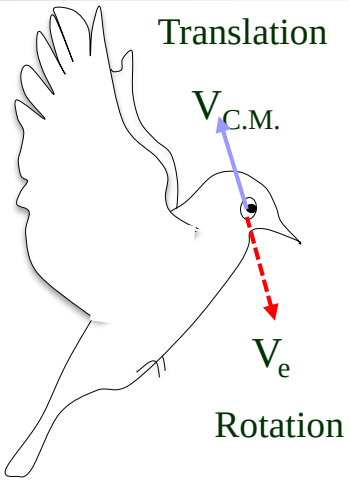
HEAD-BOBBING IN PIGEONS

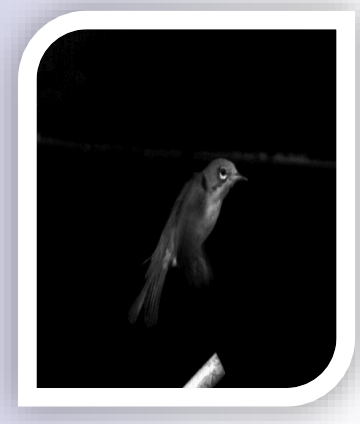
"Head-bobbing" is characterized by a rapid forward movement (thrust phase) which is followed by a phase where the head keeps its position with regard to the environment but moves backward with regard to the body (hold phase).

R. Necker, 2007, J Comp

# 視覺穩定機理 懸停時眼睛速度定量分析



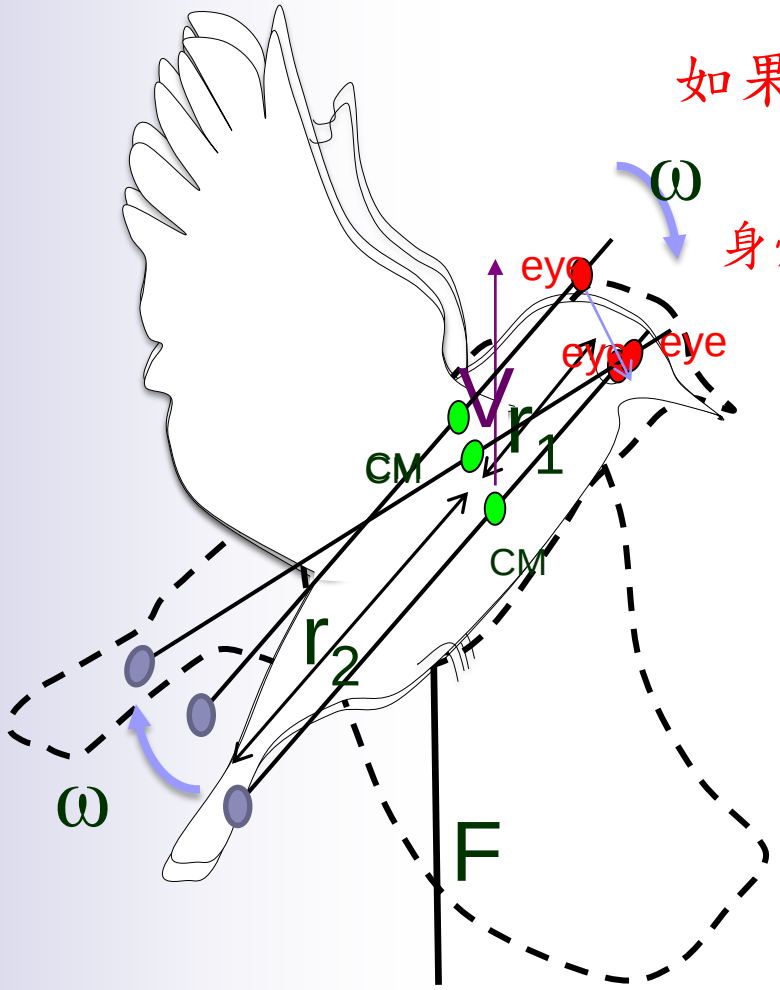
- $V_{C.M.}$與$V_e$的量值同級
- $V_{C.M.}$與$V_e$的變化趨勢一樣
- Ve與V差距平均16.8%

⇩

眼睛穩定

# 懸停下的視覺穩定機理

蘇健元論文, 台大機械博士班, 2011




如果身體的位移與旋轉在眼睛抵銷

身體看似繞著眼睛轉 ➡ 視覺穩定

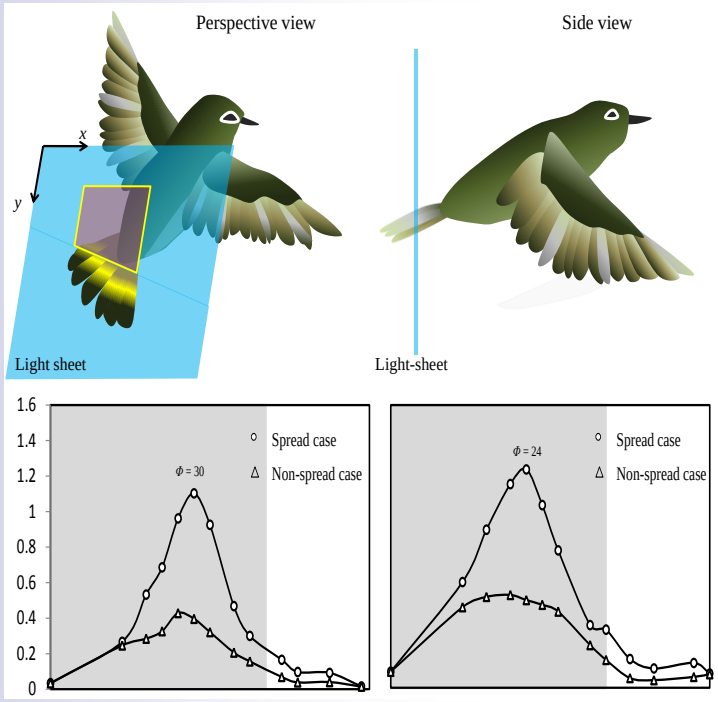
$$V_e = \omega \times r_1$$

# Spread tail for recovering posture

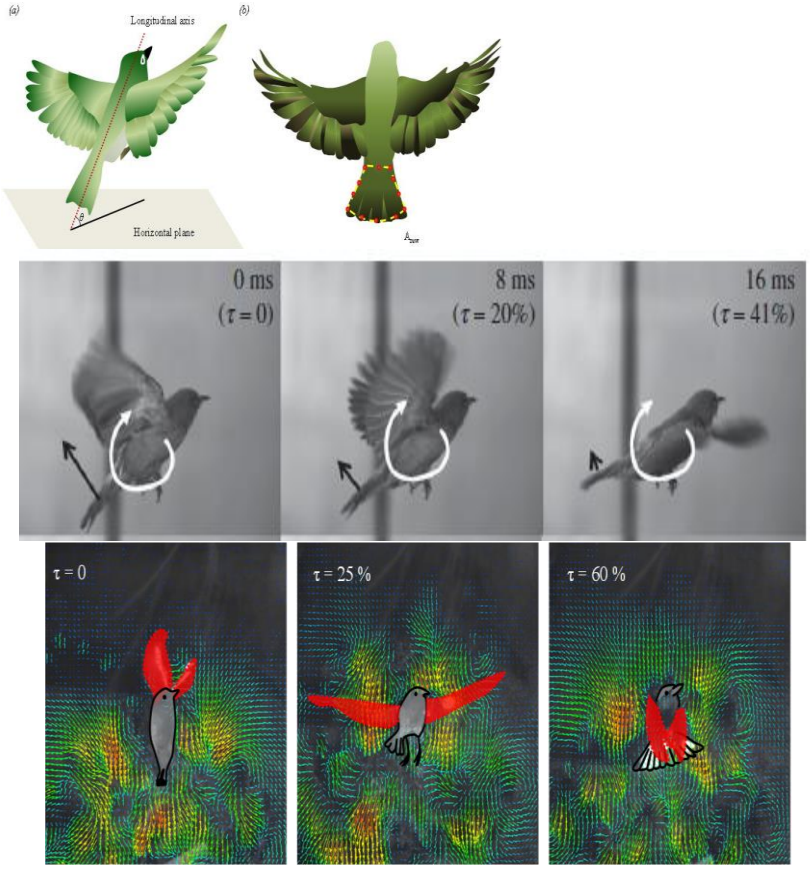
# A passerine exploits tail spreading to facilitate quick recovery of body posture during hovering

Y. C. Su, S. C. Ting, Y. H. Chang, and **J. T. Yang***

***J. Royal Society Interface***, Vol. 9, pp. 1674-1684, 2012



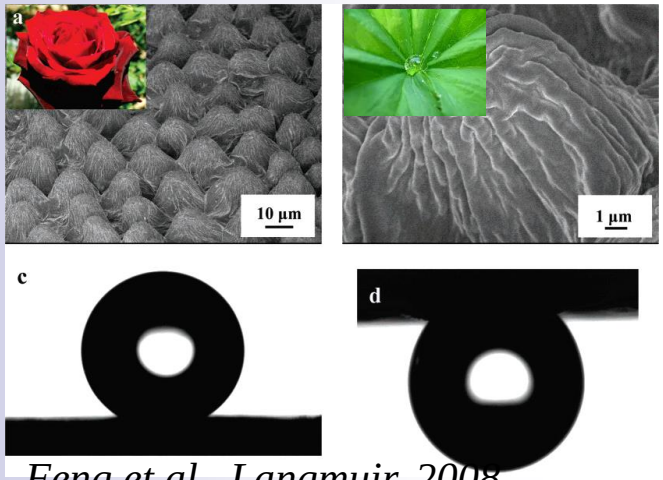

*Variation of forces experienced by the spread and non-spread tails during a wingbeat cycle.*



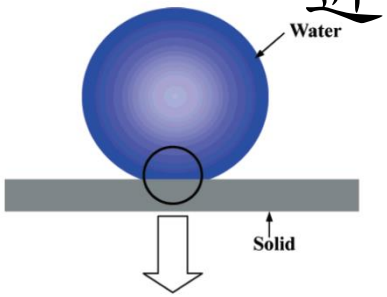

We demonstrate and analyze how a passerine exploits tail spreading to facilitate quick recovery of body posture during hovering flight. The spreading of the tail will give rise to a more rapid recovery of the body posture because greater forces are experienced.

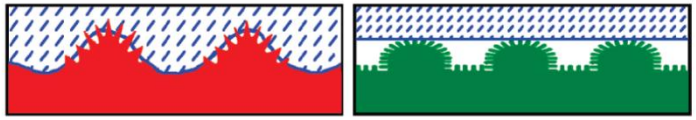
# 仿生研發策略與步驟

近商品之




*Feng et al., Langmuir, 2008.*



Petal (Cassie impregnating wetting state)　　Lotus (Cassie's state)