仿生與實驗室晶片導論- 2020

Introduction to Biomimetics (III)

昆蟲的飛行力學與仿生啟發

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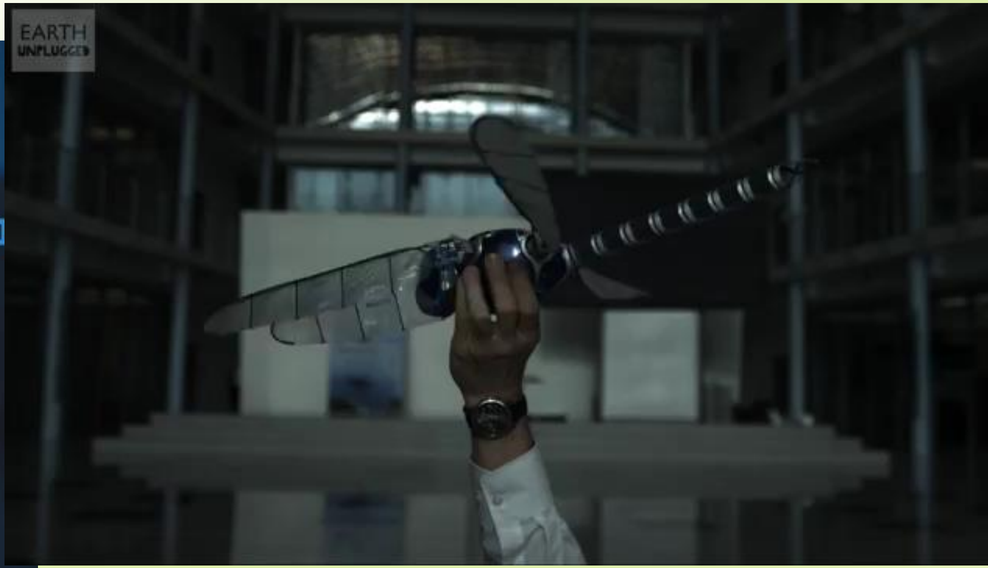
October 21st, 2020 @台灣大學應用力學研究所

festo-smart-bird

festo-butterfly

festo-dragonfly

festo-dragonfly2



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

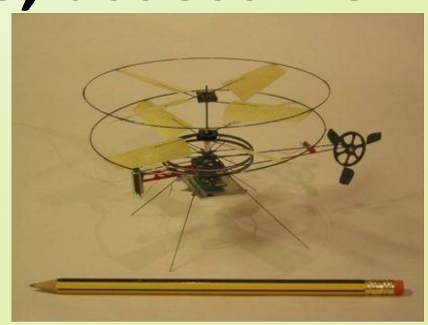
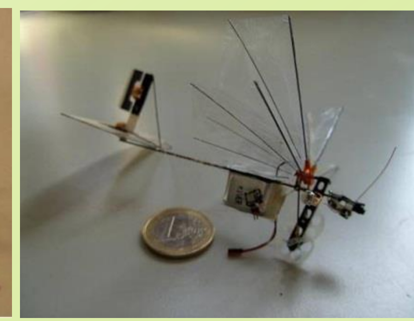
- **Max dimension: 15 cm**

  Nominal flight speed: 10 m/s

  Reynolds number regime: 10^5 or lower

  $\Rightarrow$ **monitoring, surveillance, assessment…**

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

昆蟲飛行時速比較 (朱耀沂, 2004)

蒼蠅 7~8 km/h	蜻蜓 25~40 km/h
金龜子 8~13 km/h	單帶弄蝶 16~30 km/h
飛蝗 16~20 km/h	小灰蝶 19~26 km/h
蜜蜂 20~22 km/h	大黃蝶 20 km/h
天蛾 18~40 km/h	非洲粉蝶 10~13 km/h

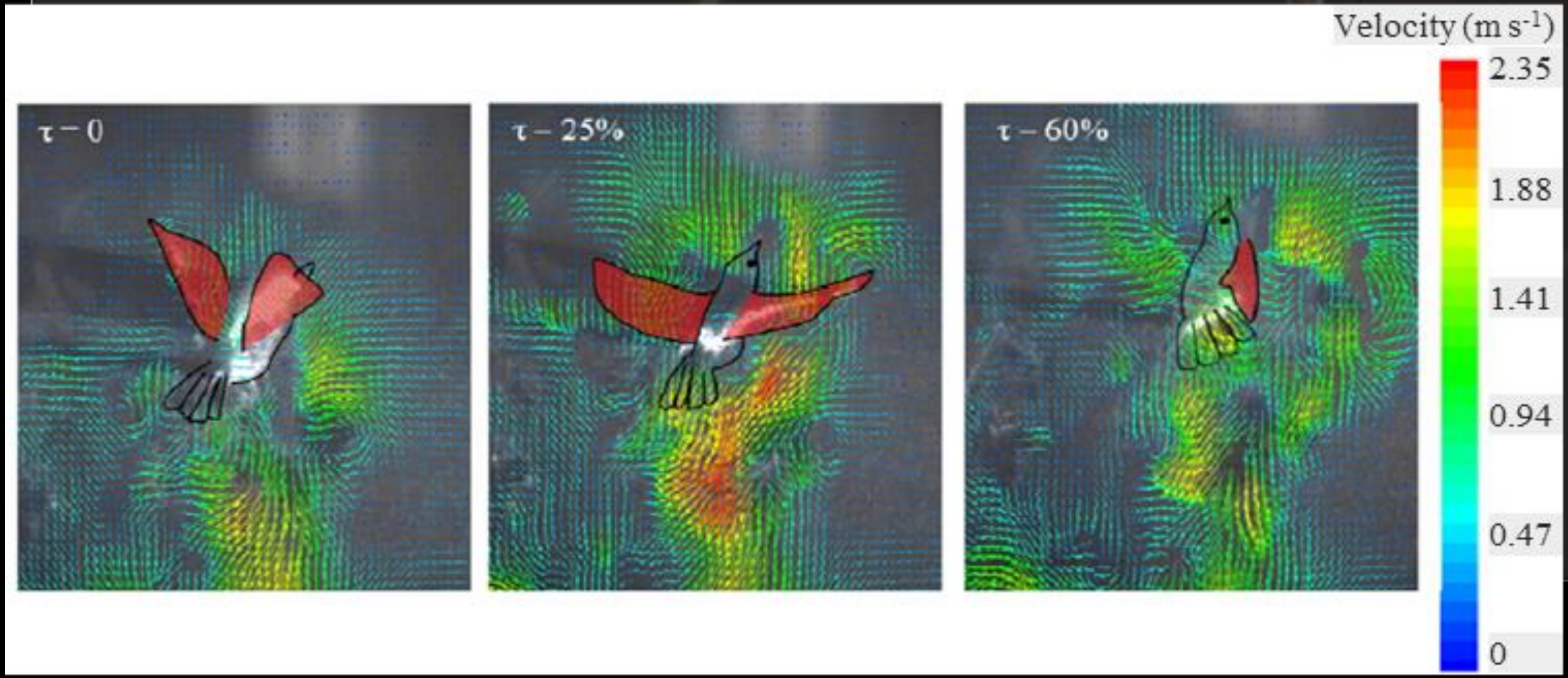
仿生飛行 (Biomimicry Flight)

觀察生物

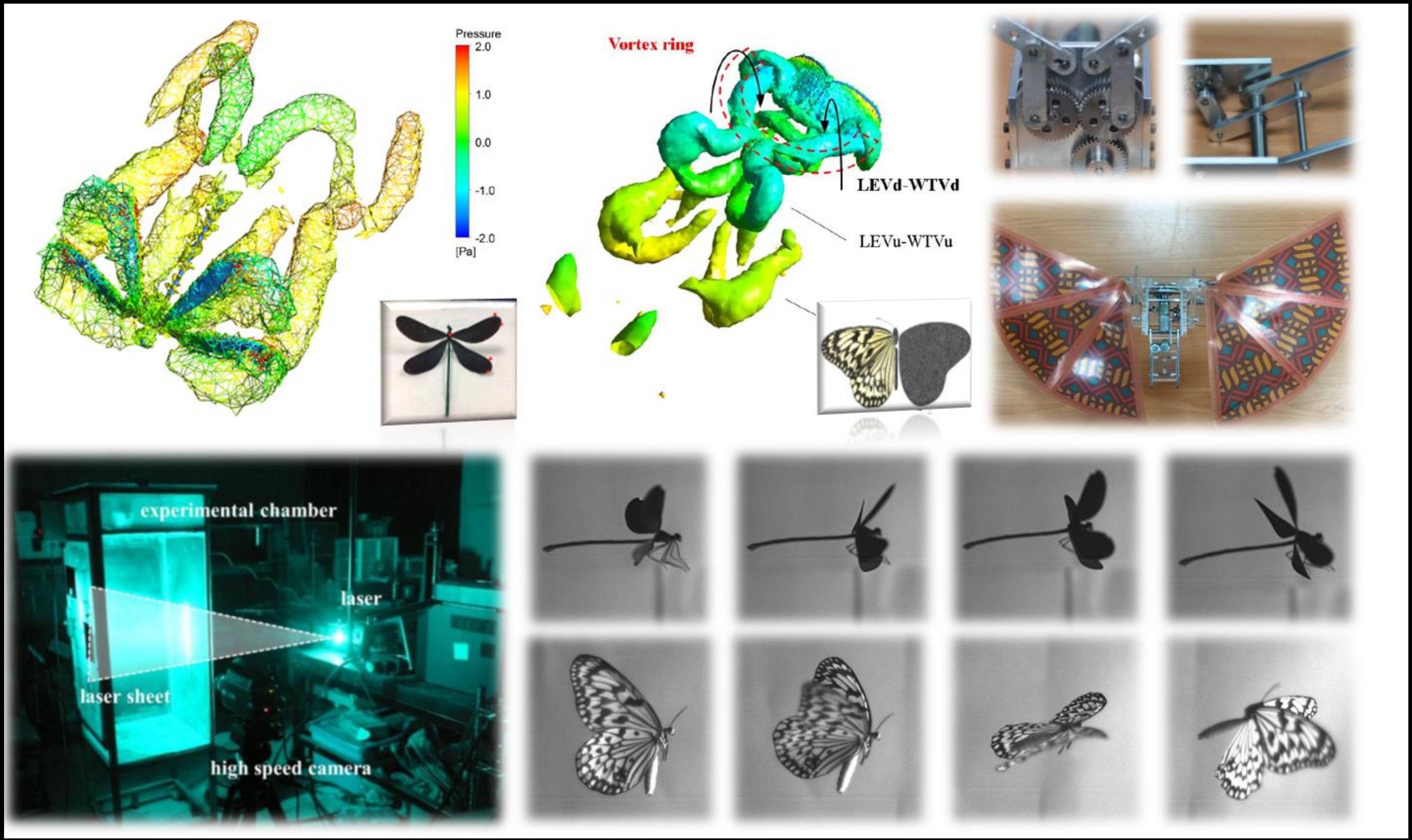
解析原理

模擬/應用

從生物的飛行尋找能幫助人類開發下一代飛行器的靈感



昆蟲飛行操控機制與仿生飛行器機構之設計開發



Maneuverable Flight Strategy of Insects and Design of Insect-like Flight Robots

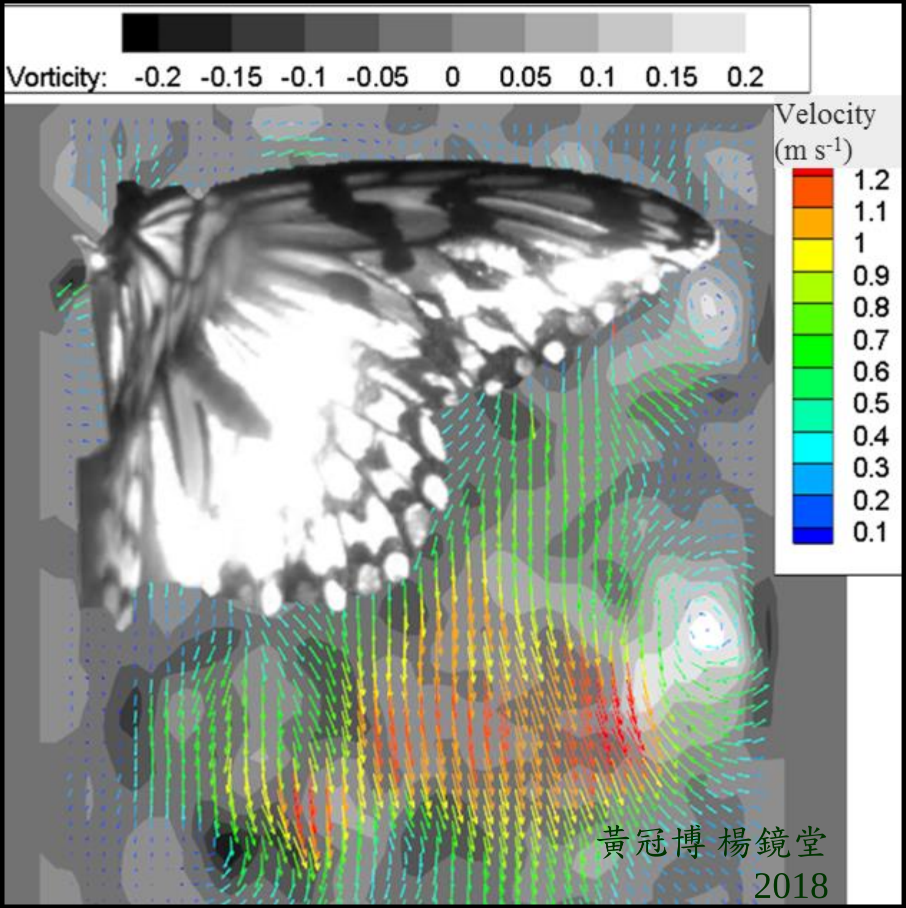
國立台灣大學機械系熱流光束實驗室　楊鏡堂教授

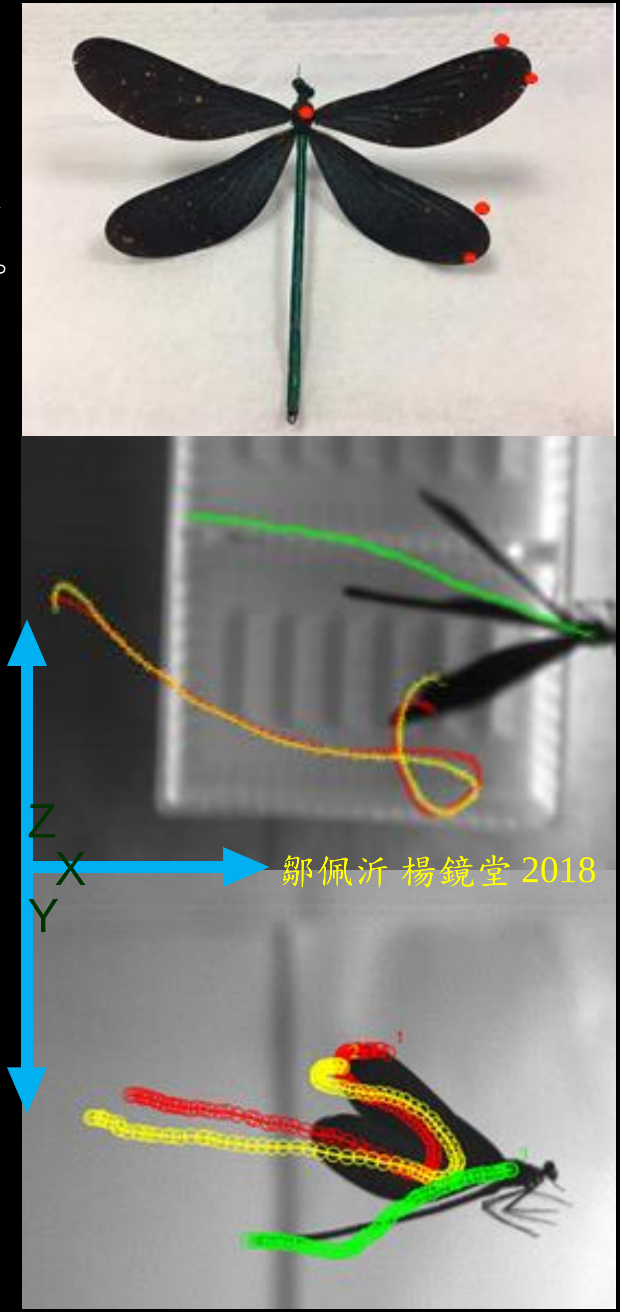
生物飛行動作/流場解析

生物飛行頻率高，速度快，透過高速攝影機觀測與粒子影像測速法(Particle Image Velocimetry, PIV)，本實驗室得以剖析生物的飛行。生物飛行比固定翼飛機複雜，主要依兩個方向深入剖析:

1. 拍翅動作
2. 流場渦旋結構

解析原理





蝴蝶流場PIV分析 (↑)

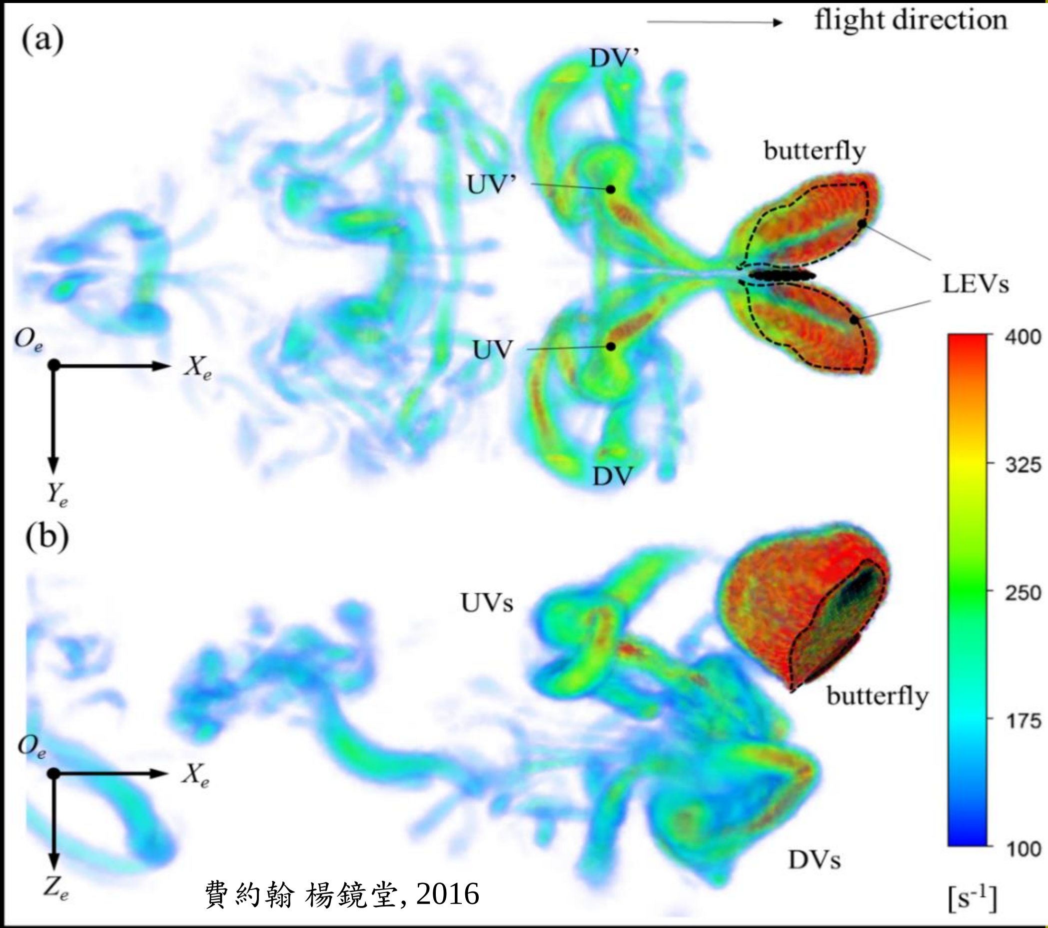
豆娘飛行動作分析 (→)

BEAM Lab

數值模擬流場分析

（←）豆娘流場數值模擬

（↓）蝴蝶流場數值模擬

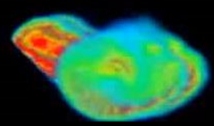


分析歸納後，提出生物的飛行假說，為了後續機構設計的精準性與控制成本，先以數值方法模擬，進行初步的驗證.

數值模擬/機構開發

top-view

side-view



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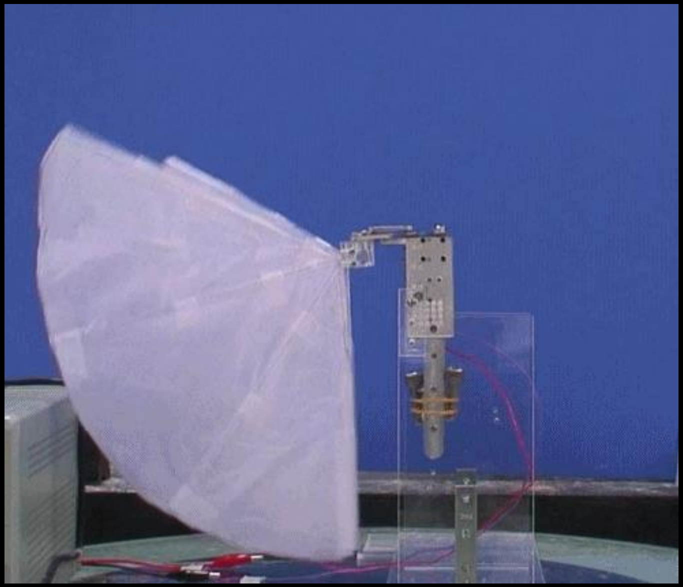
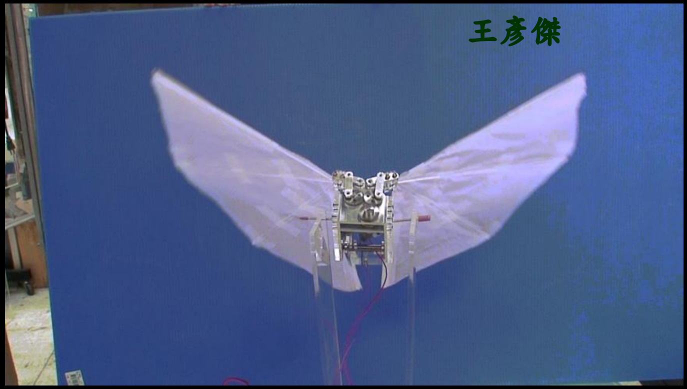




蝴蝶流場數值模擬（↑）
機器蝴蝶動作驗證（→）

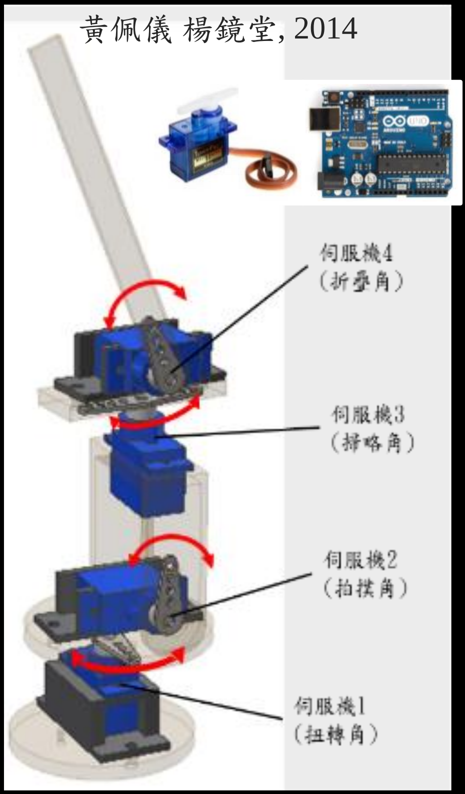
觀察生物
↓
解析原理
↓
模擬/應用

經過分析後，提出生物的飛行假設，並加以驗證

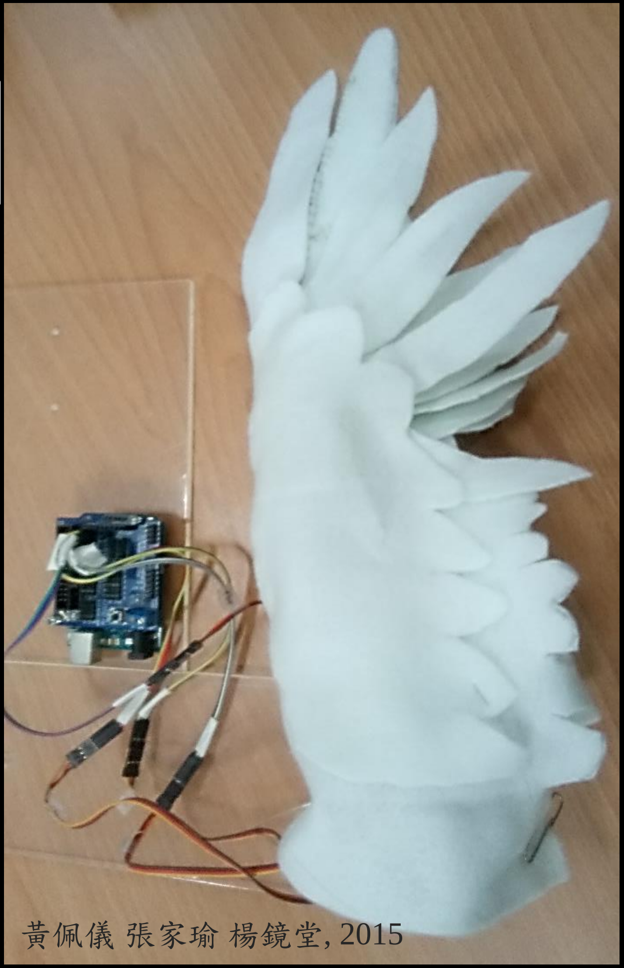
驗證的方式主要為 (1). 數值模擬　(2).機構實驗

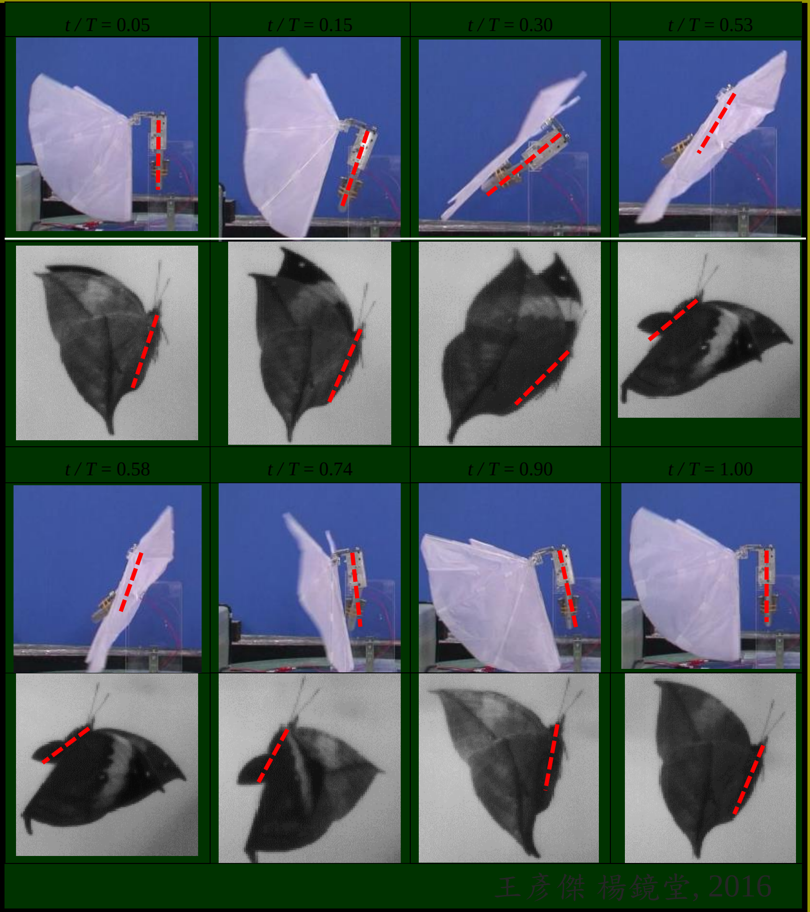
機構開發與動作驗證

模擬分析後，開發對應的機構驗證，與生物比較



黃佩儀 楊鏡堂, 2014


黃佩儀 張家瑜 楊鏡堂, 2015

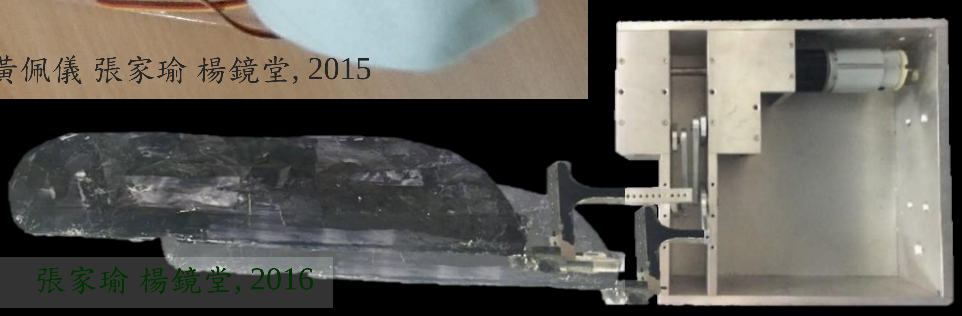


王彥傑 楊鏡堂, 2016

(↑) 機器蝴蝶動作驗證

(←) 仿鳥翅膀驗證機構

(↓) 豆娘蜻蜓拍翅機構


張家瑜 楊鏡堂, 2016

觀察生物

↓

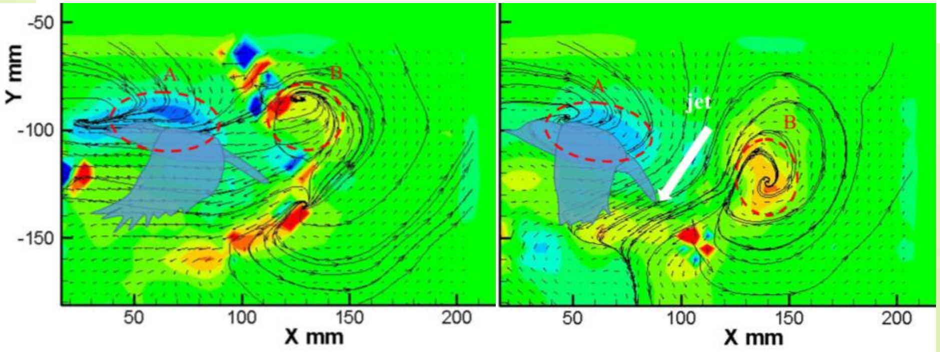
解析原理

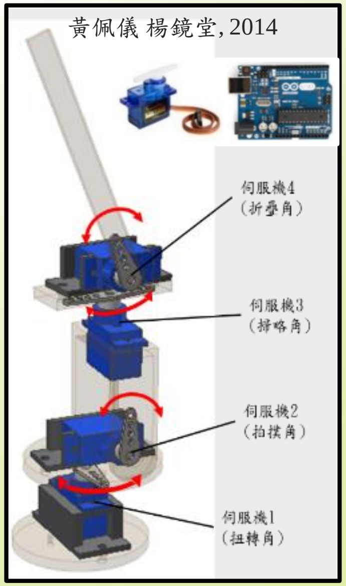
↓

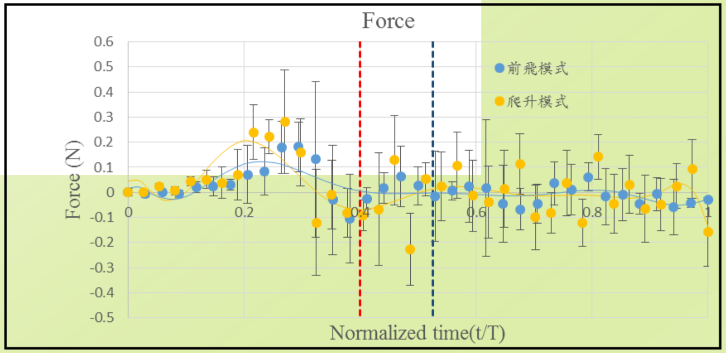
模擬/應用

Analysis of the Mechanism of the Forward Flight in Japanese White-eye and Design a Bird-Mimicking Mechanical Flapper

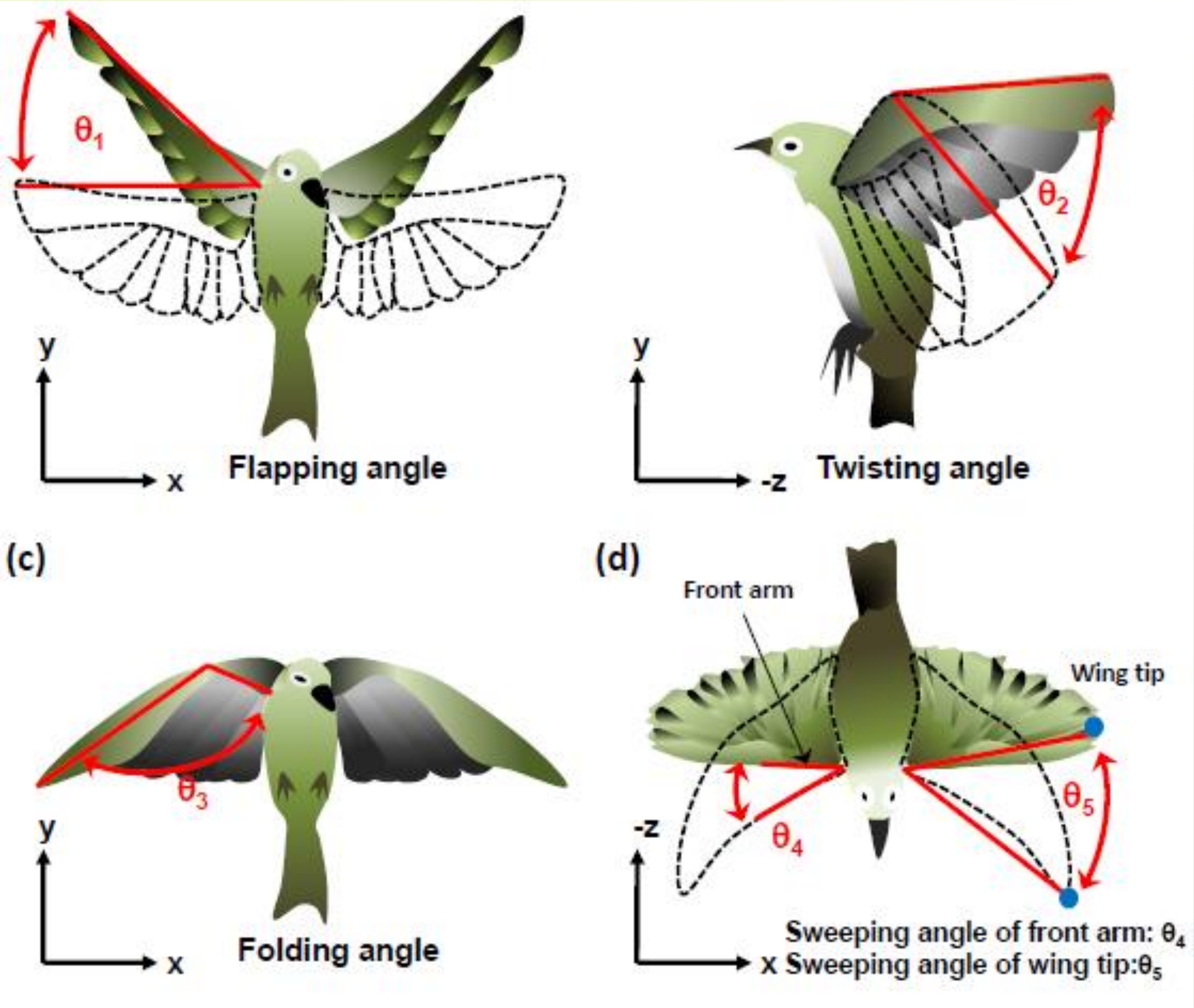
葉思沂 黃佩儀 費約翰 楊鏡堂, 2016 航太研討會最佳論文獎







Terminology



仿生飛行 (Biomimicry Flight)

NASA: Marsbee - Swarm of Flapping Wing Flyers for Enhanced Mars Exploration

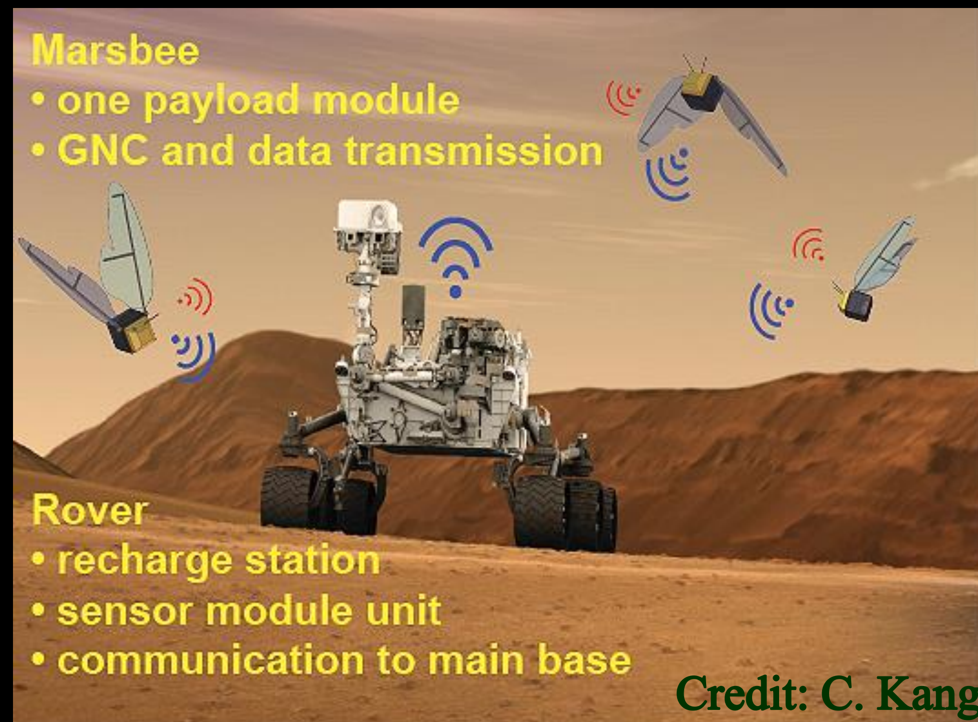
觀察生物

↓

解析原理

↓

模擬/應用

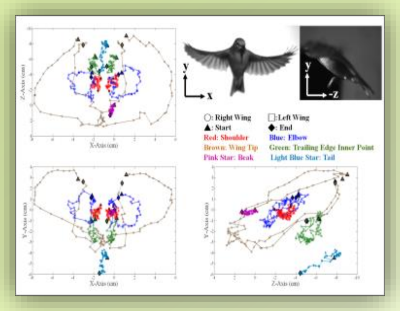


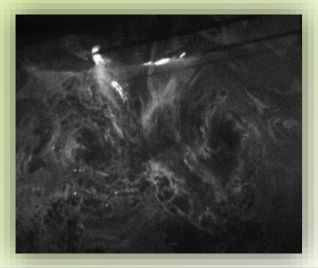
目的：從生物的飛行尋找能幫助人類開發下一代飛行器的靈感

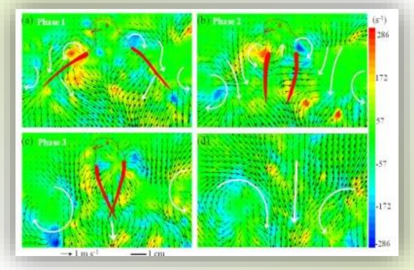
應用：微飛行器開發 (MAV, Micro Air Vehicle, DARPA, 2005)

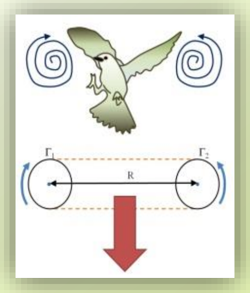
DARPA, 2011 *DARPA Nano Air Vehicle (NAV) program*

Beam Lab 研究策略暨歷程





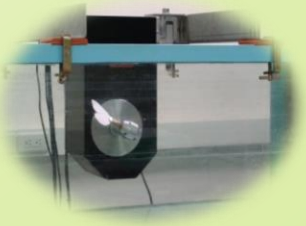




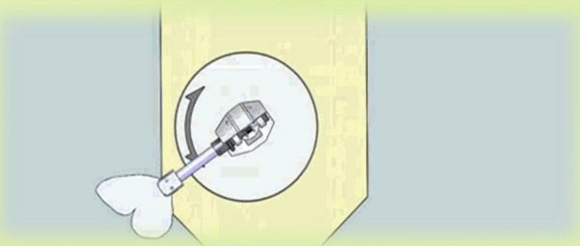
Flight Mechanics & Biophysics
(2008-2014)

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

Artificial Design & Test
(2013-2017)



Biomimetic Vehicles



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。

昆蟲飛行 why?

昆蟲 vs. 飛機與直升機

1. 拍撲翼機動性高，操縱靈活，可在短時間內改變方向 (可瞬間產生相當自身體重10倍的升力，並在2~3週期內轉換方向)；然而飛機、直升機轉換方向需要較長的時間。
2. 定翼機與旋翼機藉由 Kutta condition 產生升力，而拍撲翼除了 Kutta condition 外，還有翅膀加速和減速所產生的暫態效應，分別為翼前緣渦漩貼附、尾流捕獲、附加質量效應、旋轉環流量效應。透過這些暫態效應，昆蟲可以用很小的功耗產生很大的升力，例如蝴蝶的長途遷徙 (帝王斑蝶可長途遷徙 4000 km、青斑蝶從日本飛到台灣)。
3. 由於 Kutta condition，定翼機與旋翼機由於需要足夠的速度才能建立升力，例如飛機起飛需要很長的跑道做加速；然而昆蟲相反，昆蟲可從靜止狀態做瞬間起飛，如採蜜時，可從一株花朵短距離精準移動到另一株花朵。

昆蟲 vs. 鳥類

3. 鳥類飛行時，上拍翅膀會向上拍，會產生負的升力，因此鳥類上拍時會把翅膀蜷縮起來，以降低負的升力。相反地，昆蟲則會以翼展軸做翅膀旋轉動作，透過不斷地翻轉翅膀，使下拍和上拍都能維持正的攻角。因此，昆蟲不論上下拍，都可以產生升力。此外，由於昆蟲的翅膀旋轉機制，使其能有懸停飛行模式，這是一般鳥類無法達成的(鳥類中僅蜂鳥能懸停)。

結論

昆蟲多變的飛行模式，機動性高，優越的飛行性能，使其成為近十年來微飛行器發展的主流。其微小的體積更適合運用於複雜地形探勘、救災，以及居家防護照顧上。

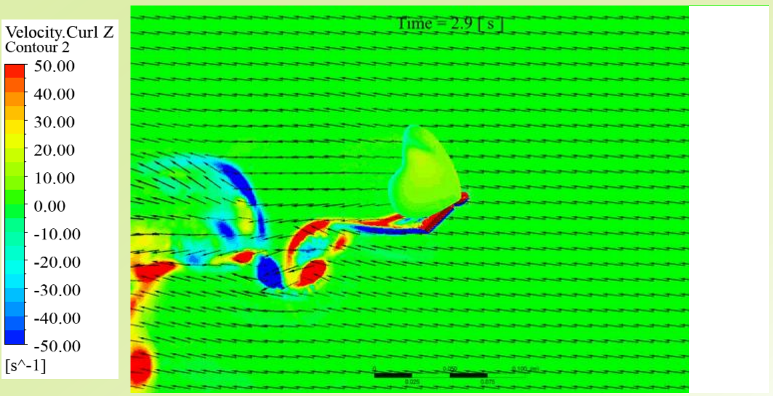
蝴蝶飛行為何非要搖擺 ?

https://www.youtube.com/watch?v=D6WbyC_f8ak

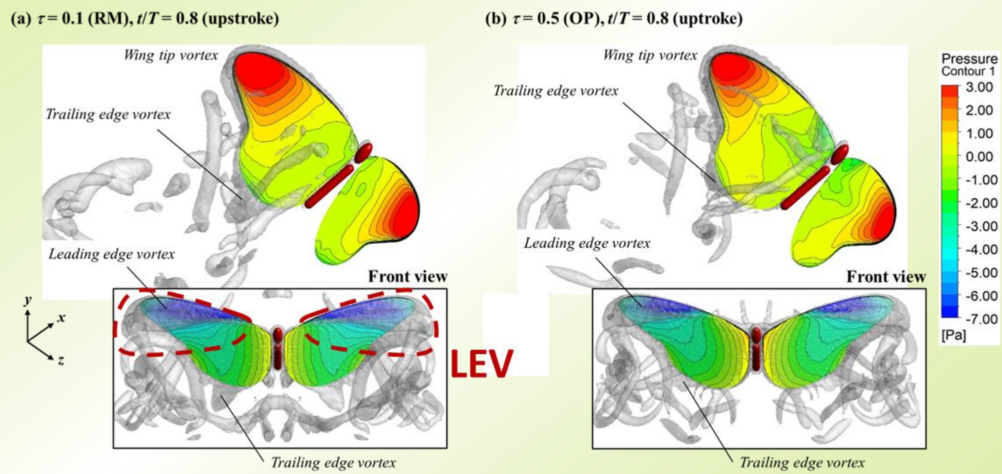
- wing motion
- abdomen motion

枯葉蝶是演化之漏網品種?

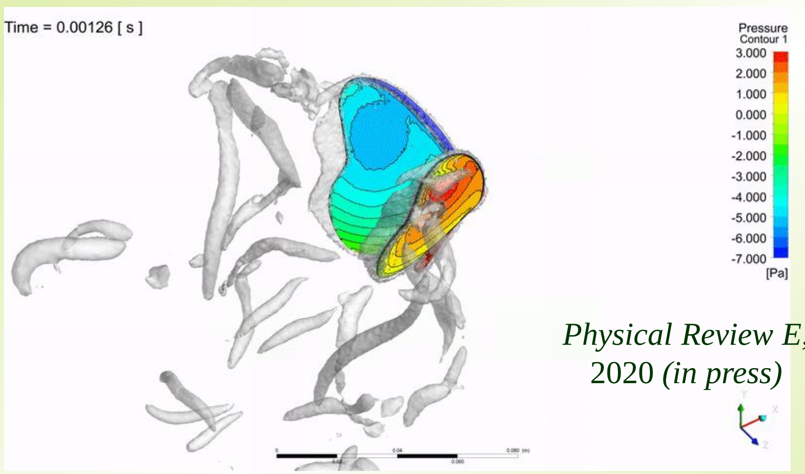
三維數值分析－ 流場、參數分析



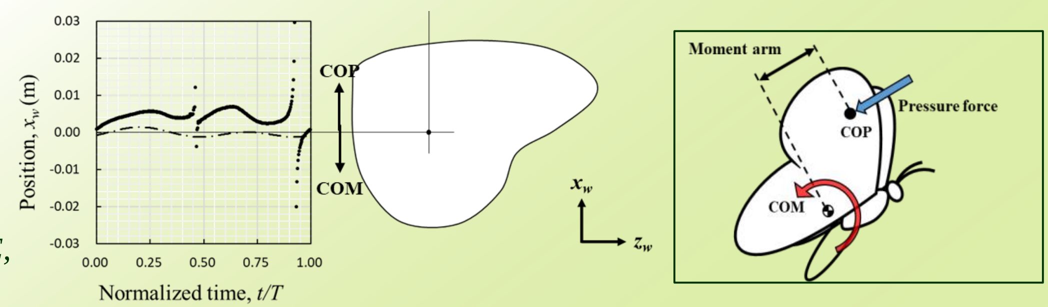
Orientation of downwash airflow.



Enhancement of leading-edge vortex (LEV). The vortex is identified by Q-criterion with Q = 30450 s^{-2}.



Physical Review E,
2020 *(in press)*



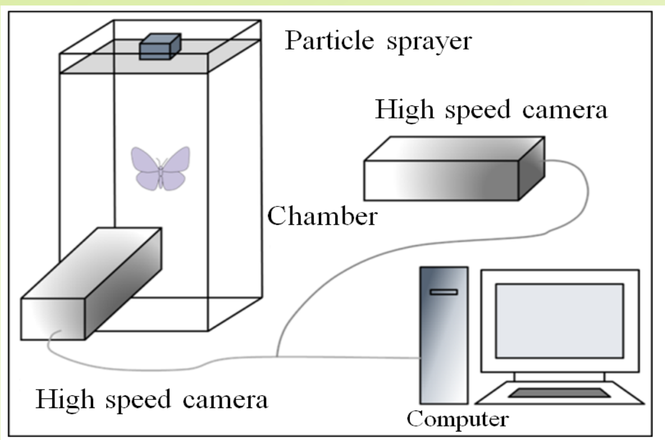
Location of the center of pressure (COP) and the center of mass (COM).

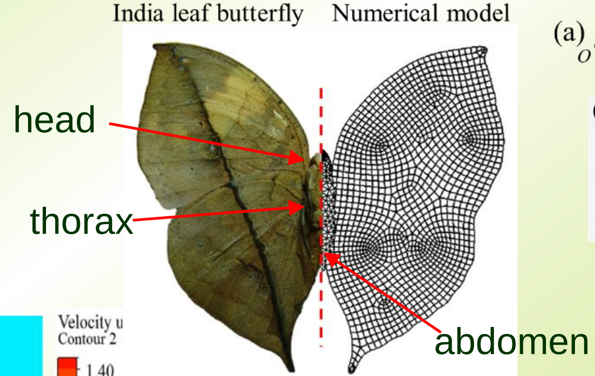
Enhanced thrust and speed revealed in the forward flight of butterflies with transient body translation (枯葉蝶)

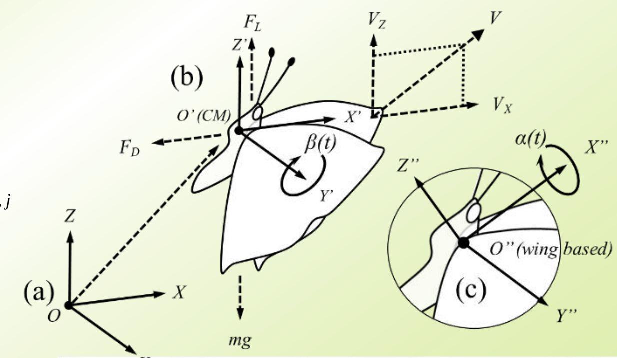
Y. H. Fei (費約翰) and J. T. Yang* (楊鏡堂), *Physical Review E*, Vol. 92, No. 033004, 2015

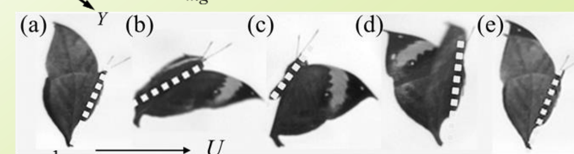
$$\frac{\partial u_{f,j}}{\partial x_j} = 0$$

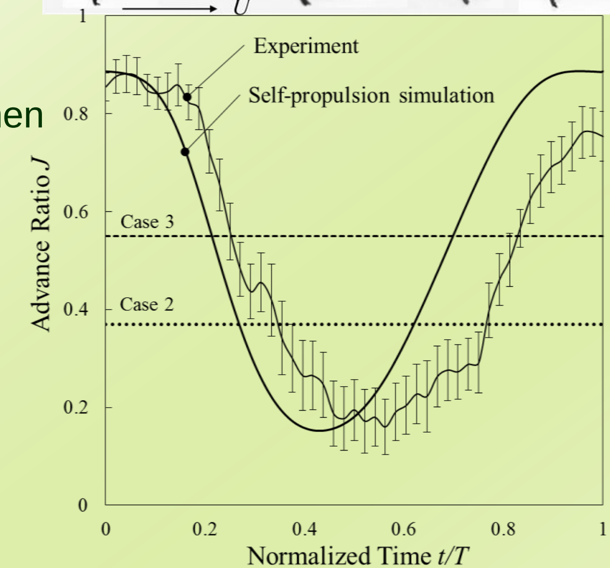
$$\rho_f\left(\frac{\partial u_{f,j}}{\partial t} + u_{f,j}\frac{\partial u_{f,i}}{\partial x_j}\right) = -\frac{\partial p_j}{\partial x_j} + \mu\frac{\partial^2 u_{f,i}}{\partial x_j^2} + \rho_f f_{f,j}$$

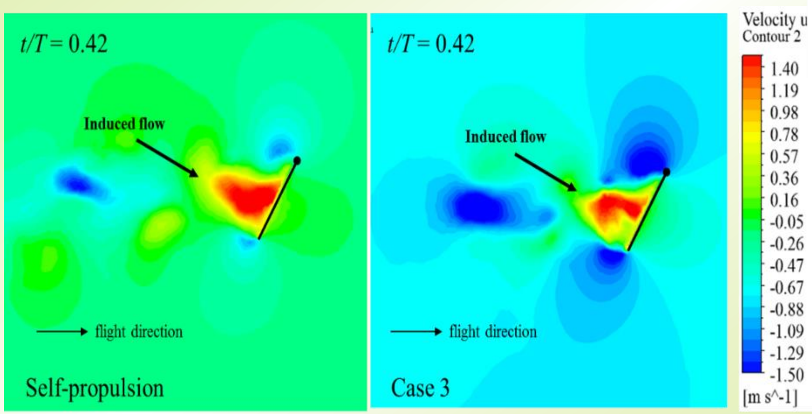


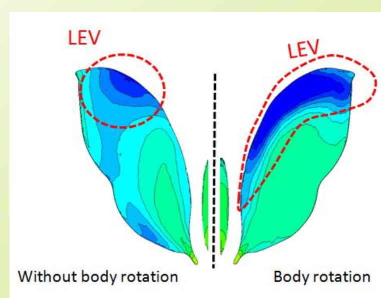








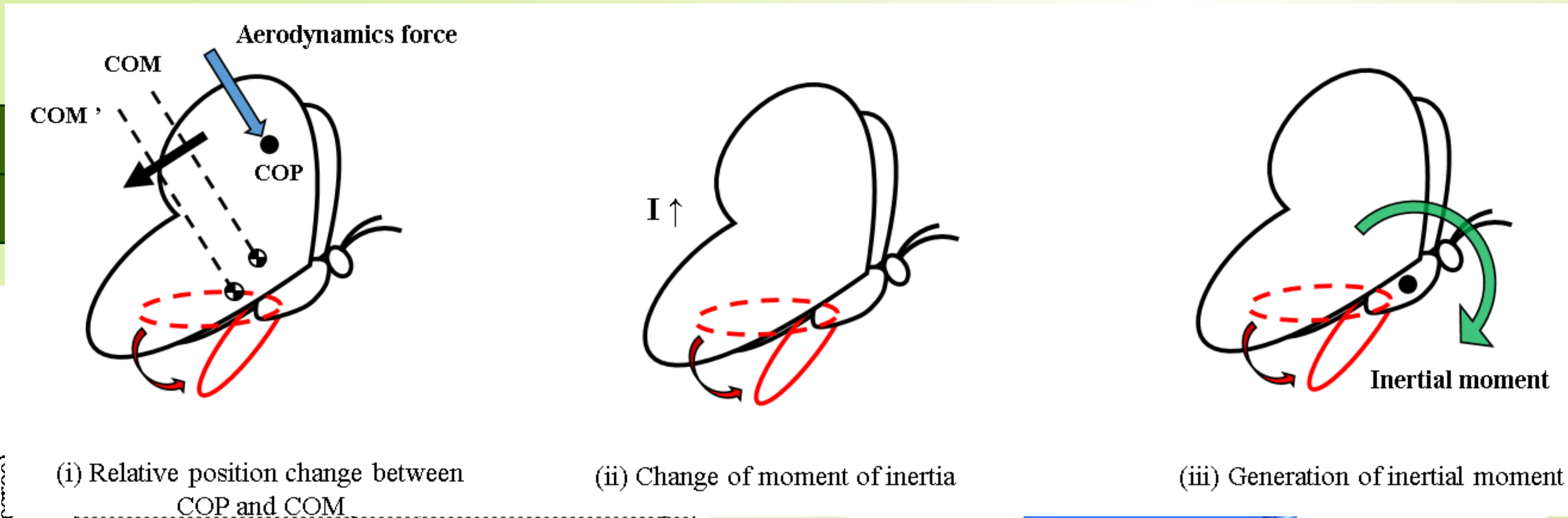


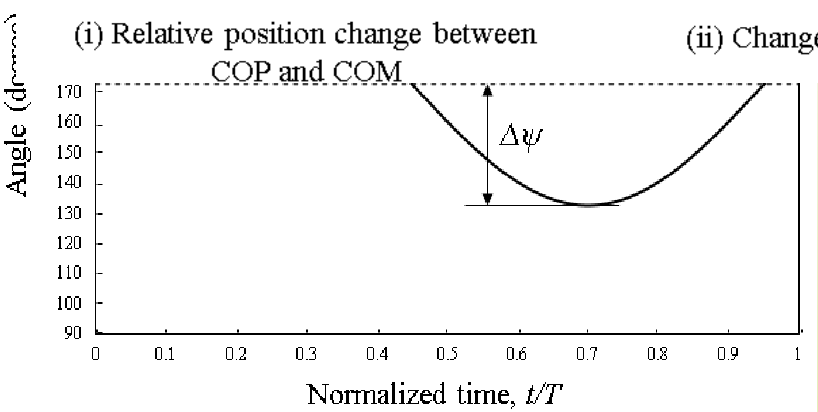


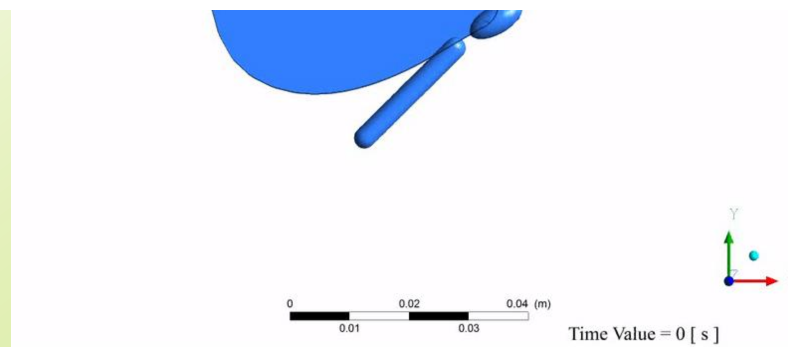
腹部擺動之效用

Adding abdominal motion

$$\psi(t) = 172.5° + \Delta\psi cos(2\pi\frac{t}{T} - 2\pi\tau))$$







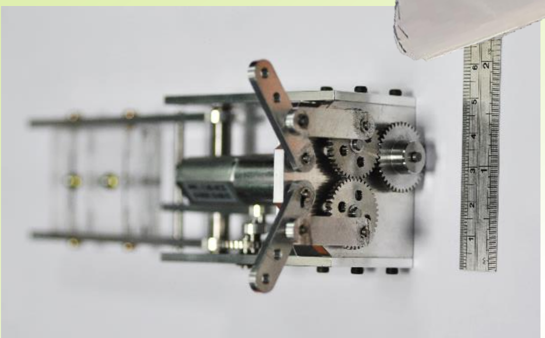
搖擺之啟發

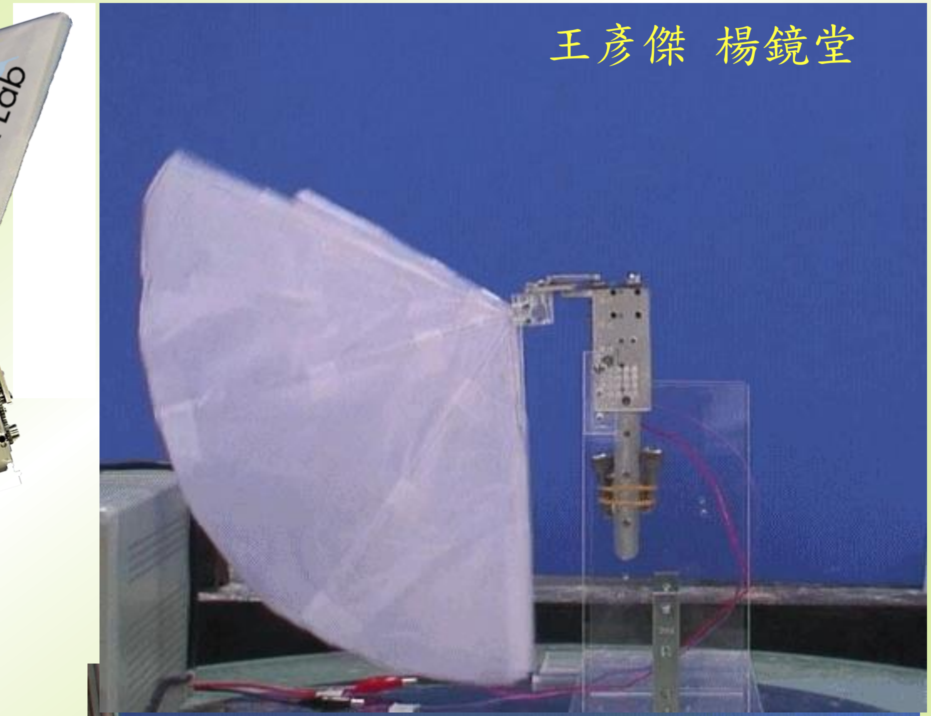
腹部擺動可以從(i)改變質量中心位置、(ii)產生慣性力矩與(iii)改變轉動慣量，三個方向影響俯仰角。其中，**慣性力矩的影響最大**，腹部擺動產生的**慣性力矩與空氣動力矩的數量級相同**。

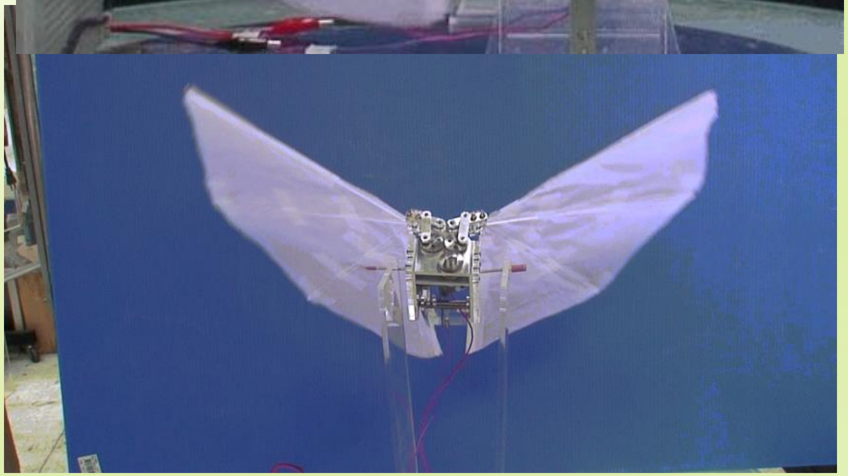
腹部擺動可產生顯著的慣性力矩，大小與空氣動力矩數量級相同，且可抑制蝴蝶的俯仰角，增加飛行的穩定性。真實蝴蝶的擺動動作可降低 20 % 的平均俯仰角加速度，而若以擺動振幅 40°、相位差 0.9 時，更可降低 60 %。

利用串聯 PD 控制，配合不同的目標函數控制腹部動態，可使蝴蝶飛出不同的軌跡。有別於先前研究，腹部擺動振幅小、消耗功率低，利用腹部擺動來操控飛行在應用上是可行的。

Beam Lab Butterfly-II





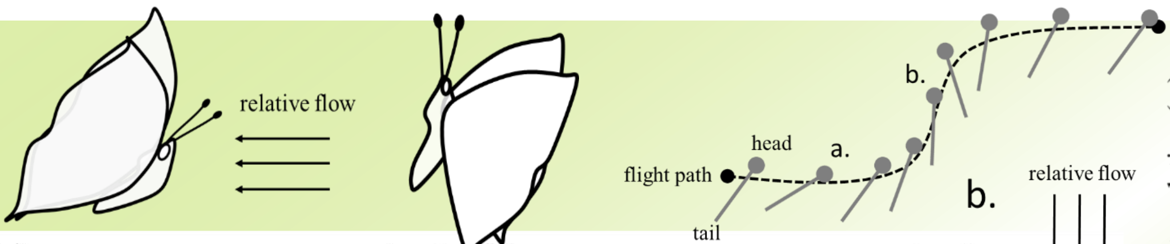


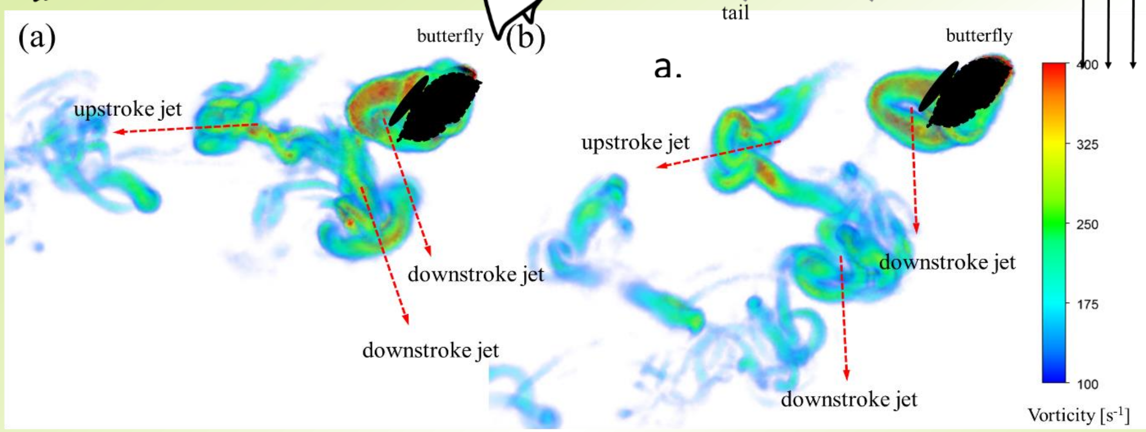
size: 5 cm × 16 cm × 3.5 cm
weight: 330 g
abdomen angle: -5˚~ 30˚
flapping angle: 55˚~ -10˚

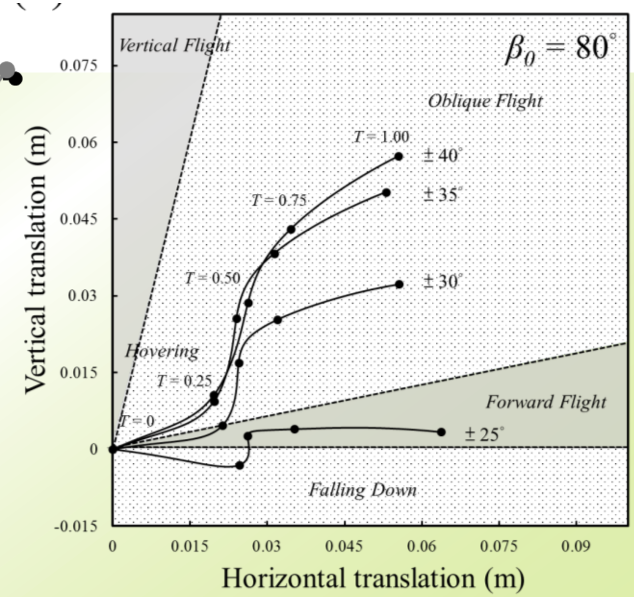
Importance of Body Rotation during the Flight of a Butterfly

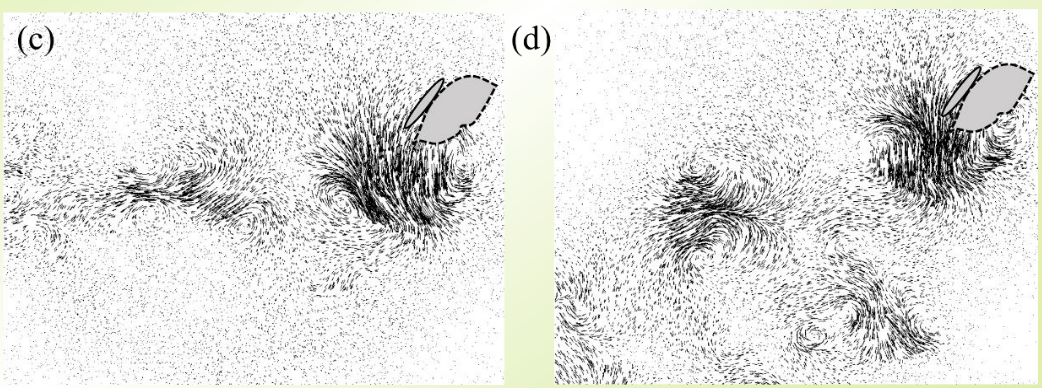
Y. H. Fei (費約翰) and J. T. Yang* (楊鏡堂)

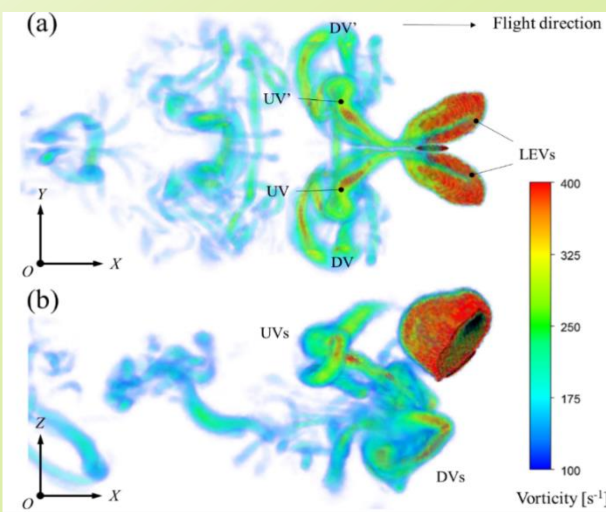
Physical Review E, Vol. 93, 003100, 2016







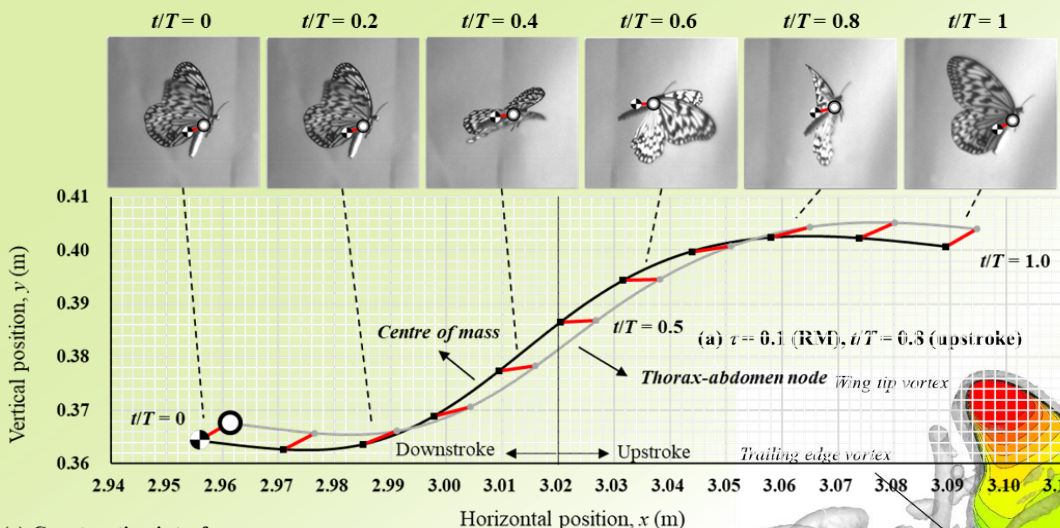


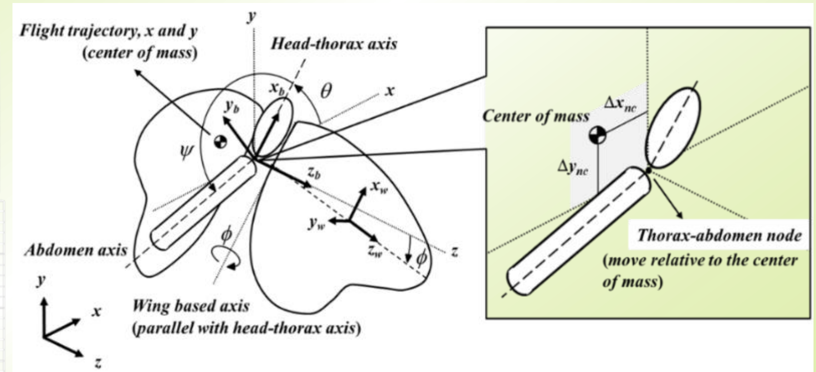


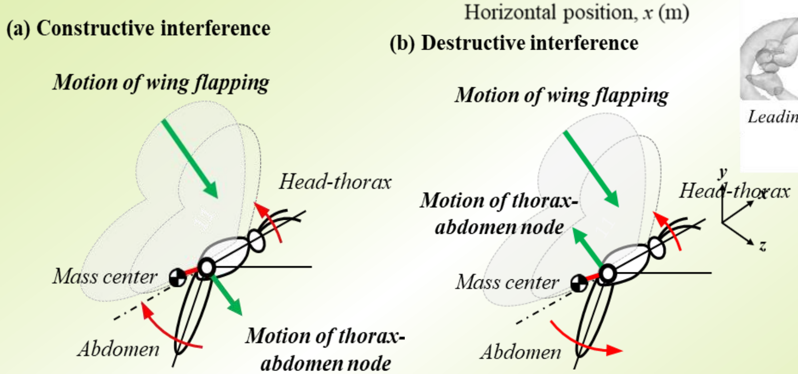
Enhanced lift and thrust via the translational motion between the thorax-abdomen node and the center of mass of a butterfly with a constructive abdominal oscillation

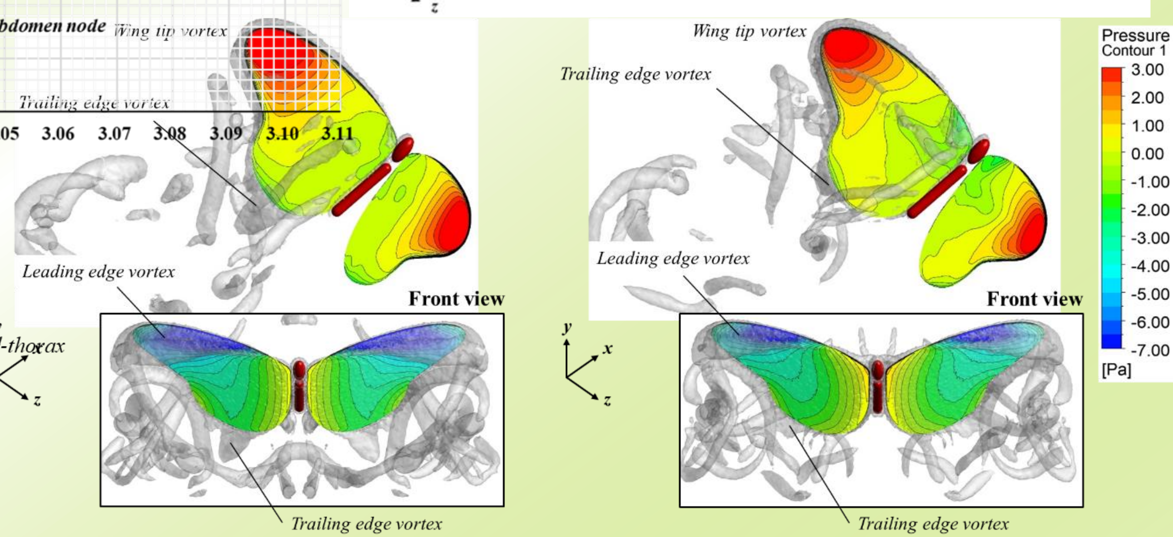
Sheng-Kai Chang (張勝凱), Yu-Hsiang Lai (賴渝翔), You-Jun Lin (林有駿), Jing-Tang Yang (楊鏡堂)*

Physical Review E*, 2020 *(in press)







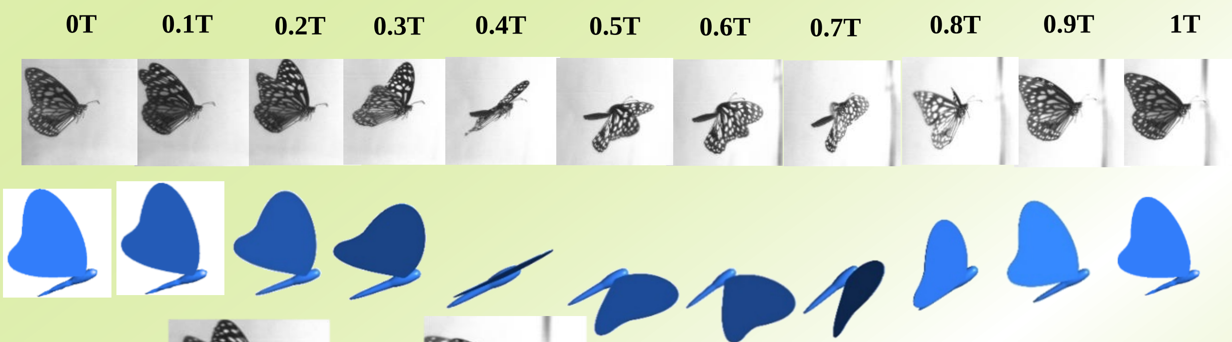


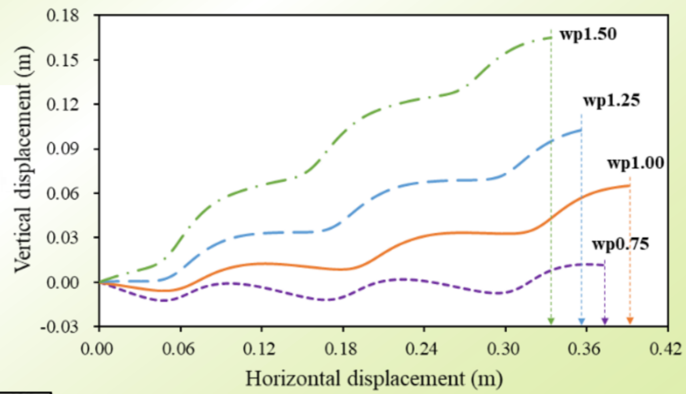
The presented mechanism reveals the effect of abdominal oscillation on coupled wing-body undulation and the resulting aerodynamic force in the flight of butterflies.

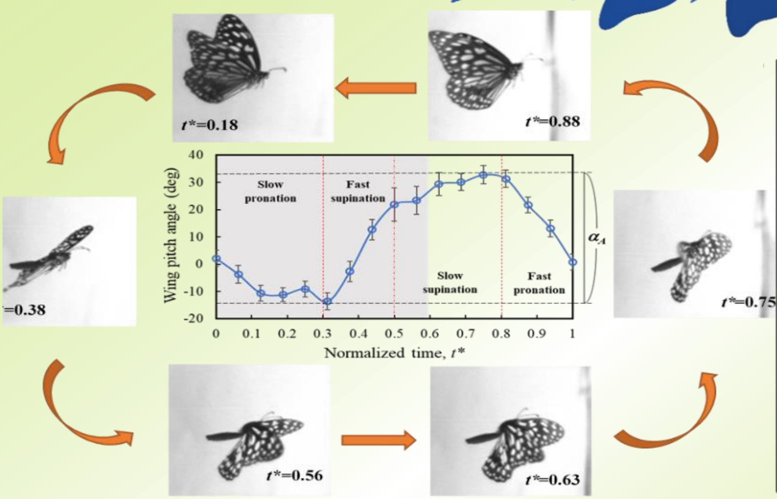
The restrained wing-pitch angle of butterfly (*Tirumala septentrionis*) for Forward Propulsion

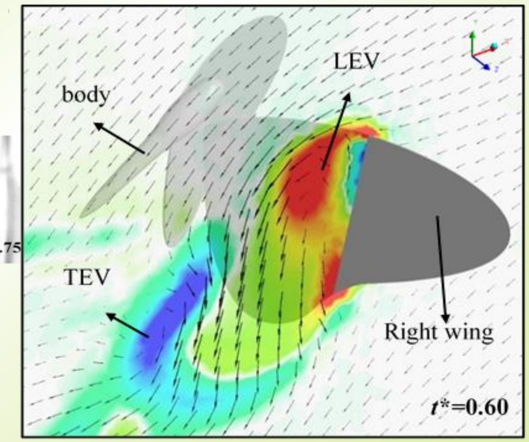
You-Jun Lin (林有駿), Sheng-Kai Chang, Yu-Hsiang Lai, Jing-Tang Yang (楊鏡堂)*

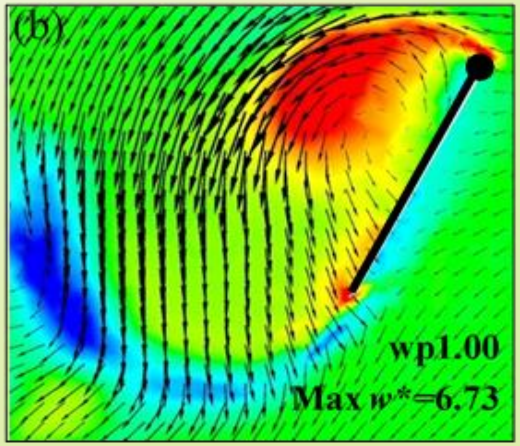
submitted to J. Royal Society Interface, 2020











From an analysis of real flying butterflies, we reveal that a butterfly generally flies in a small amplitude of wing-pitch angle in forward flight as compared with other insects. We conclude that a butterfly tends to fly with small α_A to ensure that the thrust force is not deteriorated.

為何研究豆娘?

- 觀察相似物種豆娘與蜻蜓，應用不同翅膀相位差的懸停動態，深入了解不同翅型特徵及前後翅膀交互作用對飛行表現的影響，並探討兩者分別相應於前翅領先及後翅領先相位條件下之飛行策略，以供將來四翼微型飛行器設計參考。

dragonfly

damselfly

(https://www.youtube.com/watch?v=knlXTU1R_rE) dragonfly

為何研究豆娘?

damselfly

Red Percher

(*Neurothemis ramburii*)

(a)

Formosan Jewelwing

(*Matrona cyanoptera*)

(b)

- Animalia
- Arthropoda
- Insecta
- Odonata

- Anisoptera
- Libellulidae
- *Neurothemis*
- N. *ramburii*

- Zygoptera
- Calopterygidae
- *Matrona*
- M. *cyanoptera*

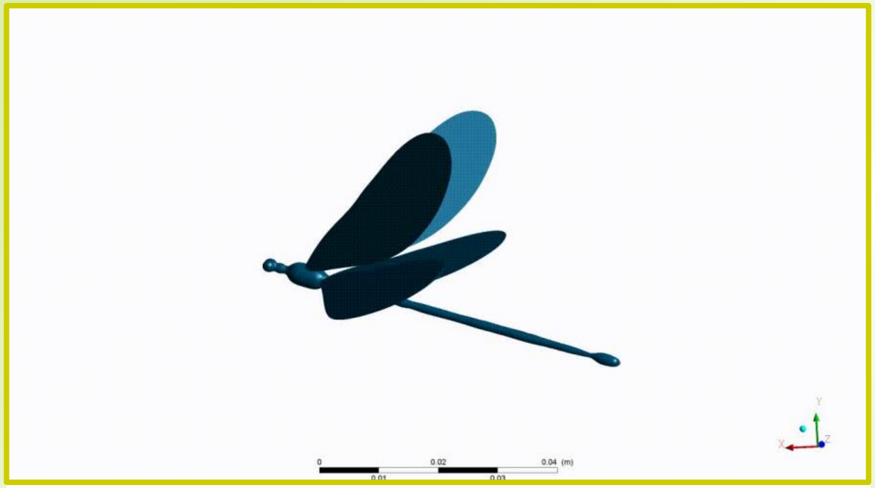
- Body length : 4.13 cm
- Wing length : 3.27 cm
- Forewing chord length : 0.81 cm
- Hindwing chord length : 1.11 cm
- Weight : 0.16 g
- Flapping frequency: 33.02 Hz

- Body length : 6.24 cm
- Wing length : 4.19 cm
- Wing chord length : 0.94 cm
- Weight : 0.14 g
- Flapping frequency: 14.33 Hz

使用生物真實動態模式之數值模擬分析

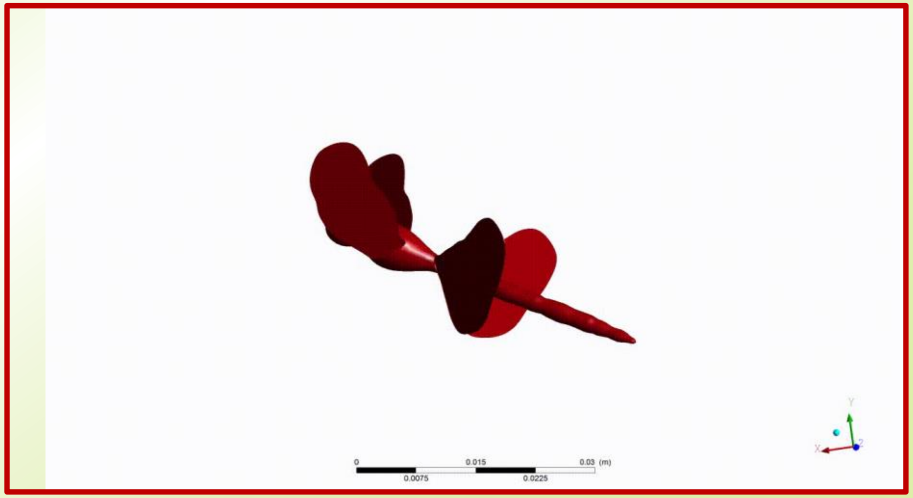
使用生物真實動態模式之數值模擬分析

- Simulation motion of **damselfly**



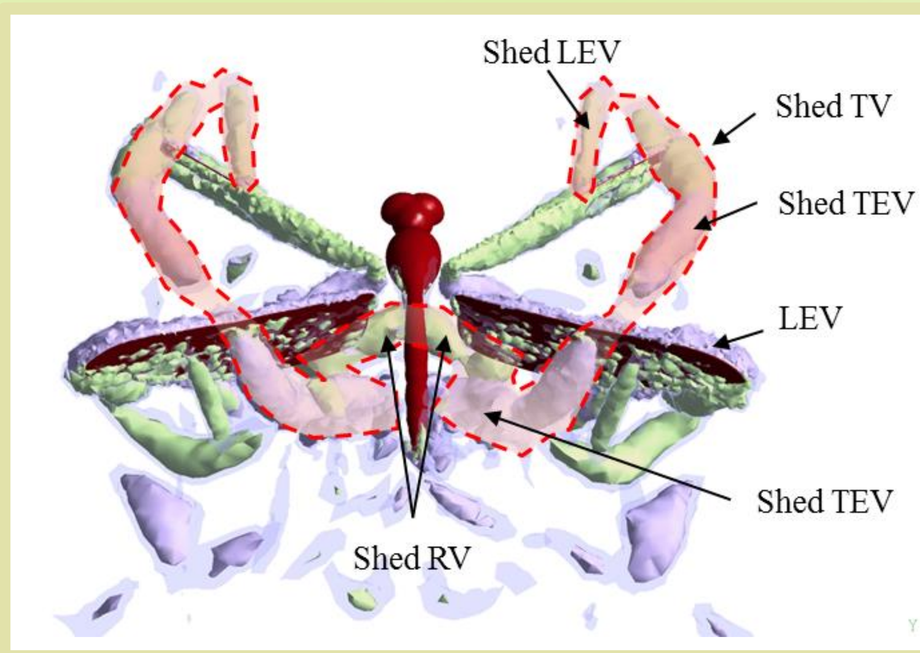
- Average vertical force produced in a stroke cycle = 1.62 mN
  (about 112 % weight of damselfly)

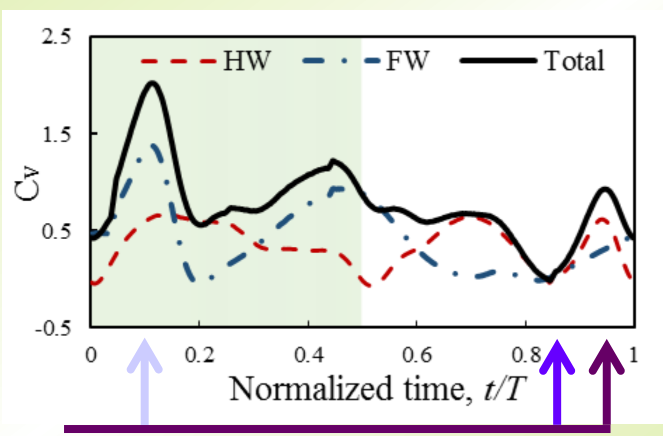
- Simulation motion of **dragonfly**



- Average vertical force produced in a stroke cycle = 1.46 mN
  (about 94 % weight of dragonfly)

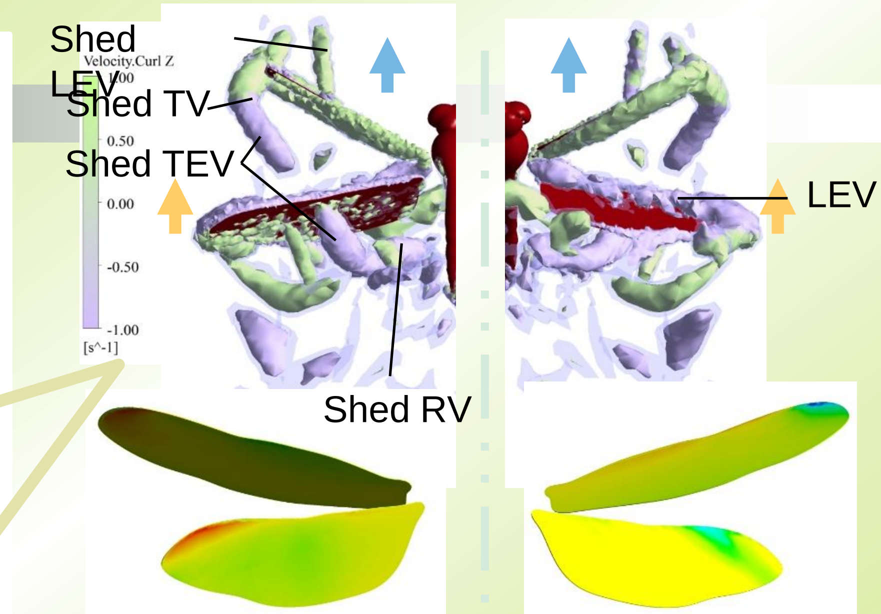
蜻蜓之飛行流場



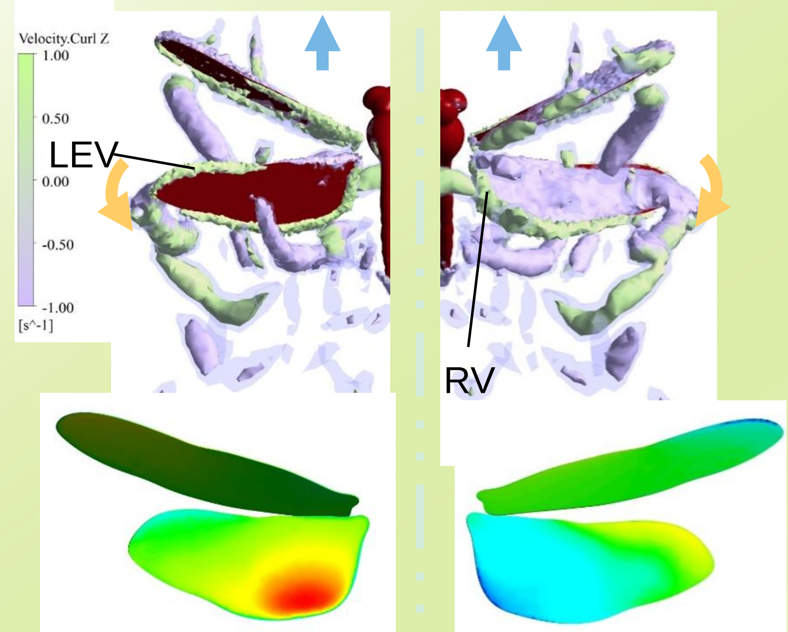


(b) Normalized time = 0.85

Back view Front view

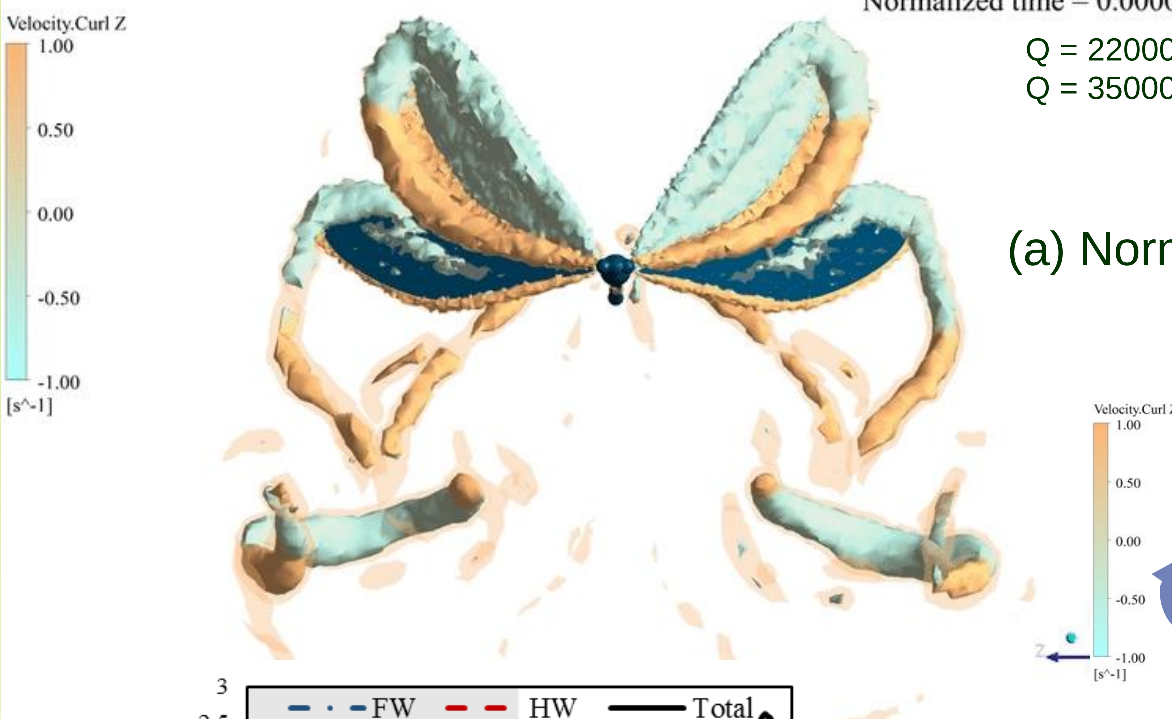


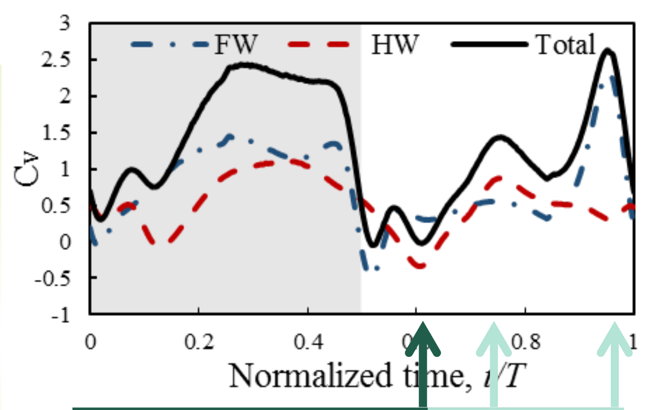
(c) Normalized time = 0.95



Flow Structure of Damselfly

Front view

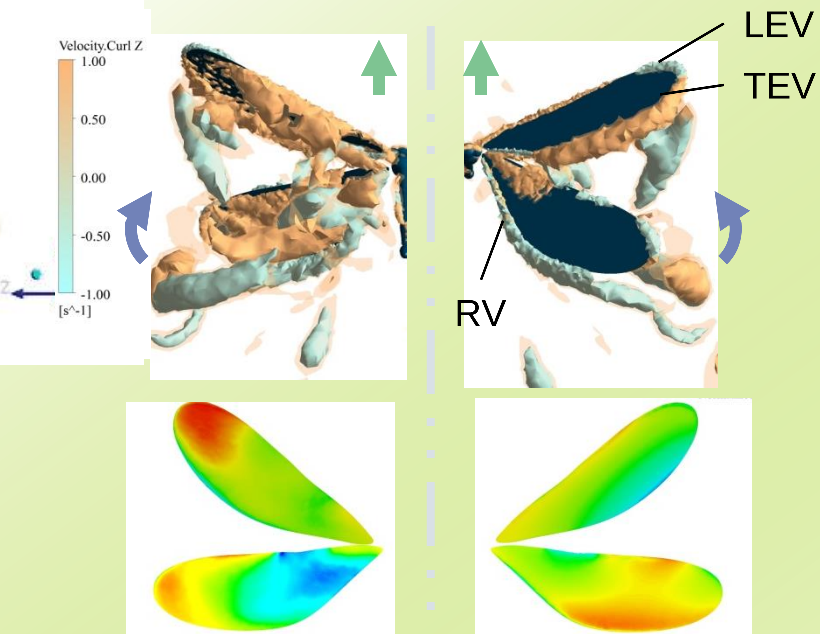




(a) Normalized time = 0.61

Back view

Front view



四翼飛行之策略 — Flight Strategy

dragonfly | **damselfly**

Red Percher

- The dragonfly's shed root vortex form a strong vortex structure trapped near the hindwing, which will impede the vertical force generation during the upstroke.

- Hovering with high rotation amplitude and longer wing rotation phase to help the root vortex separate from wing surface.

Formosan Jewelwing

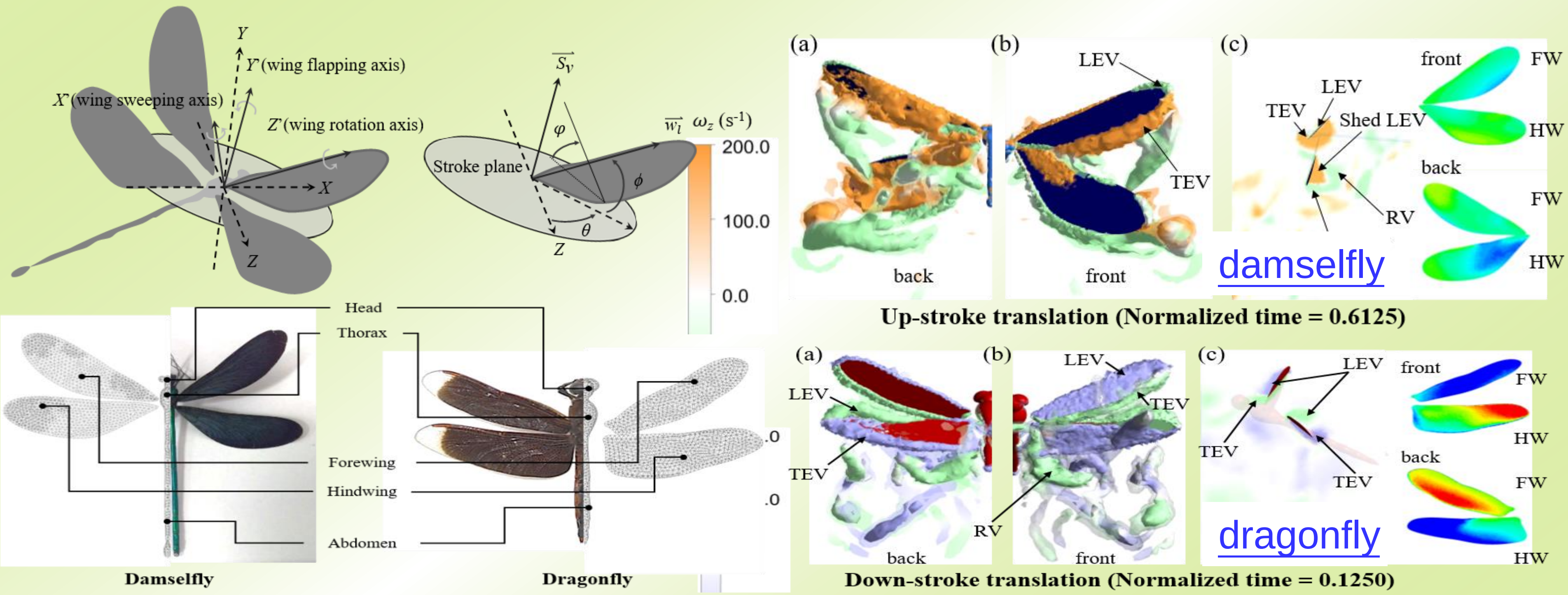
- The root vortex of the damselfly detaches rapidly and little affect the flow structure generation.

- Hovering with higher flapping amplitude and longer wing translation phase to obtain steady vertical force generation.

Effects of phase lag on the hovering flight of damselfly and dragonfly

Pei-Yi Zou (鄒佩沂), Yu-Hsiang Lai (賴渝翔), Jing-Tang Yang (楊鏡堂)*

Physical Review E, Vol. 100, 063102, 2019 (December)

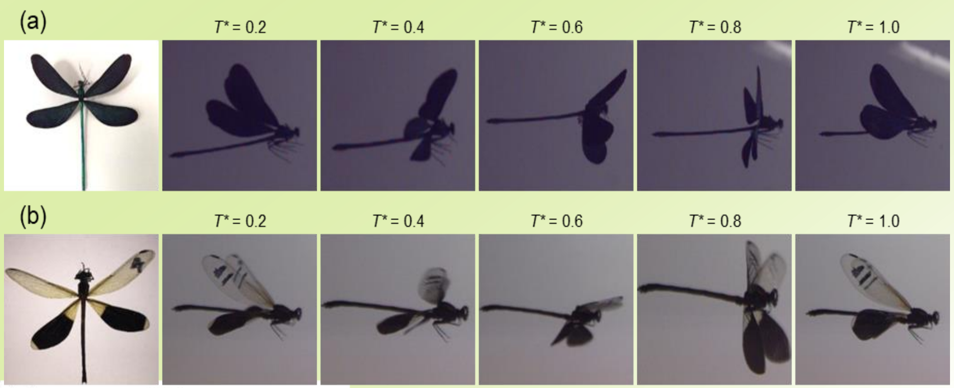


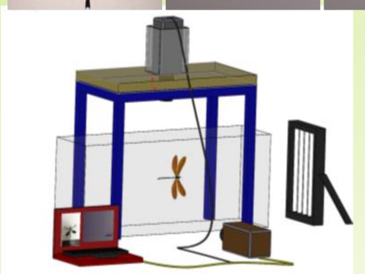
In this work we studied the differences in flight kinematics and aerodynamics that could relate to differences in wing morphologies of a dragonfly and a damselfly. These species of Odonata insects developed varied hovering strategies to fit their distinct biological morphologies.

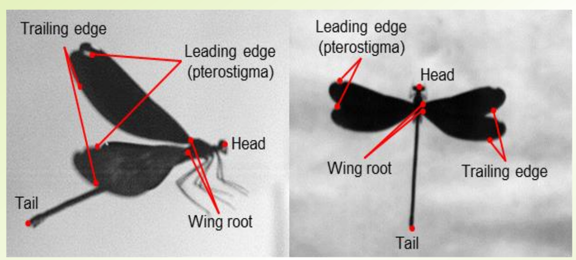
Effect of wing-wing interaction coupled with morphology and kinematic features of damselflies

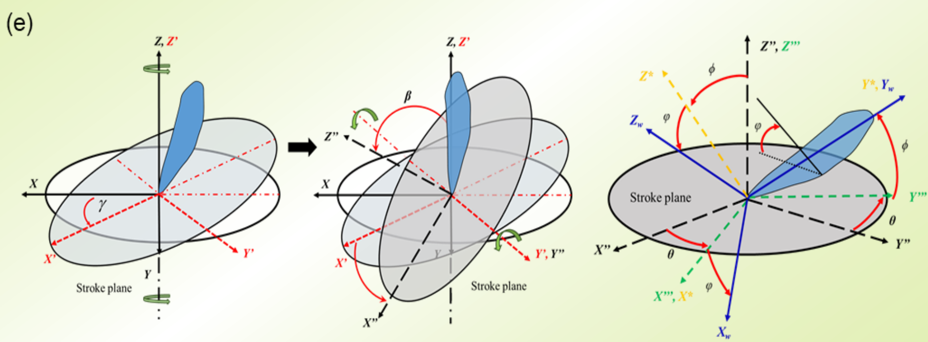
Y. H. Lai (賴渝翔), Y. J. Lin (林有駿), S. K. Chang (張勝凱), J. T. Yang (楊鏡堂)*

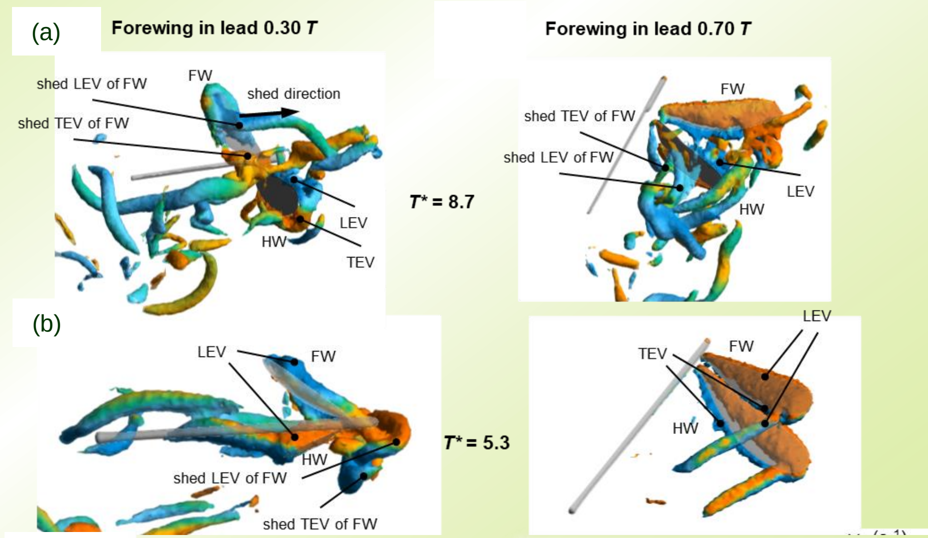
Bioinspiration & Biomimetics, 2020 (*in press*)

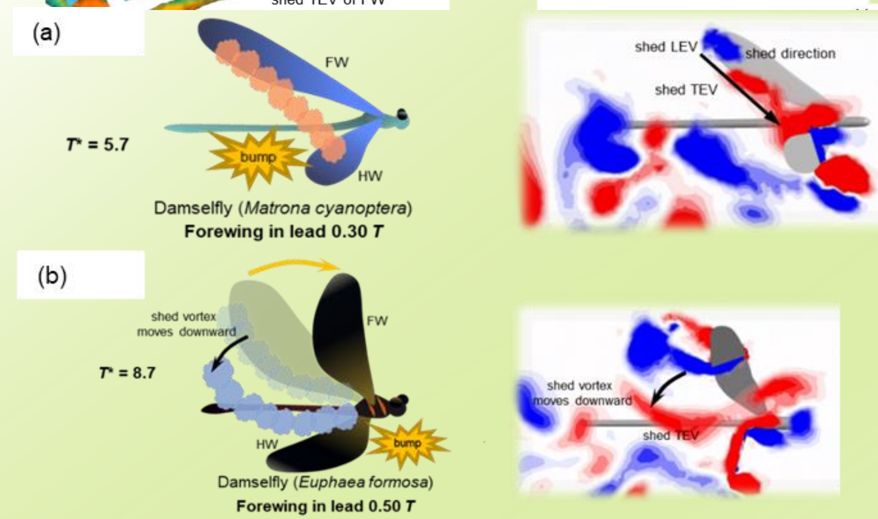












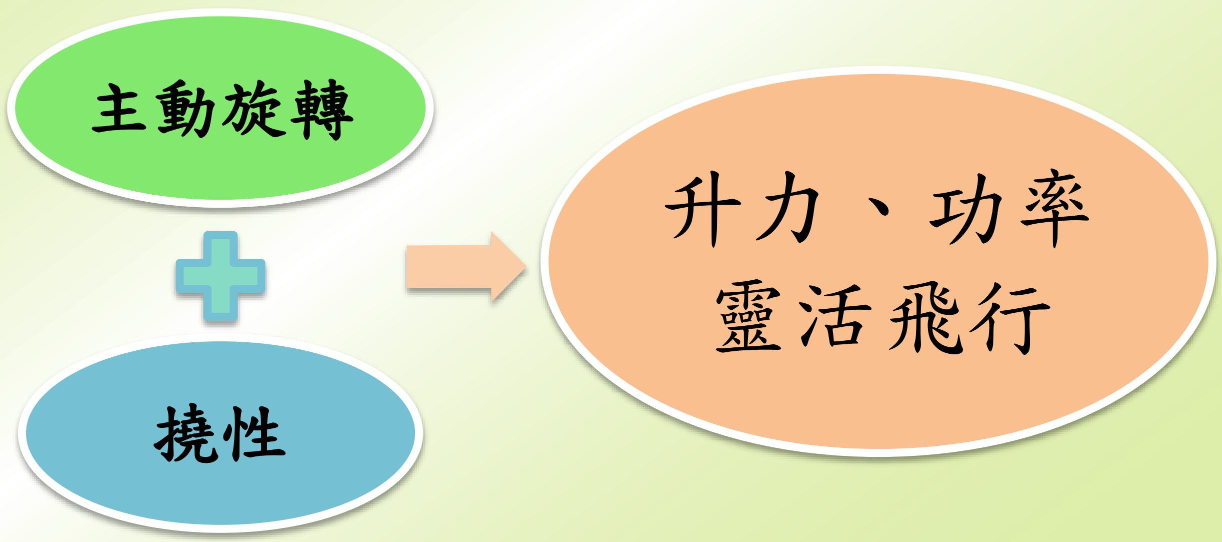
短 程 展 望

- 釐清昆蟲在不同飛行模式下之操控機制。
- 利用PIV及3-D數值模擬了解生物特質、飛行流場結構、力矩交互作用。
- 建造與改良具可操控性之仿昆蟲拍撲機構。
- 拍撲機構產生空氣作用力量測與創新設計

研究主旨－ 邱筠雅

洪千茵 (2019-2021)

以仿大白斑蝶(*Idea leuconoe*)之拍撲機構，探討控制旋轉角主動旋轉及翅膀撓性被動旋轉的有無，以有無主動旋轉及有無撓性相互配合，研究對於前飛升力的影響，提供飛行器設計及飛行策略參考。



BEAM Lab

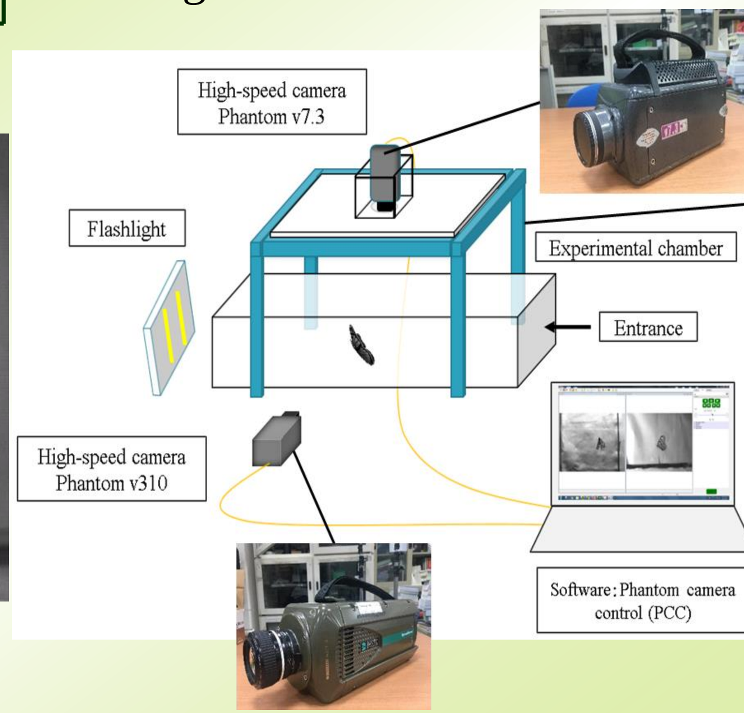
邱筠雅碩士論文，2020/07
撓性與旋轉角於大白斑蝶及仿蝴蝶拍撲機構升力之影響

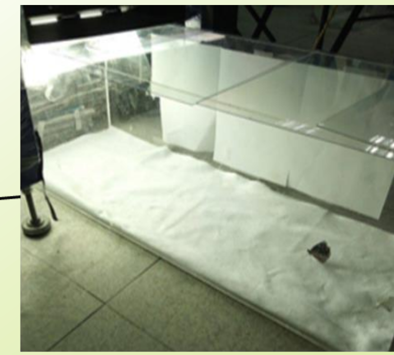
觀察與量測

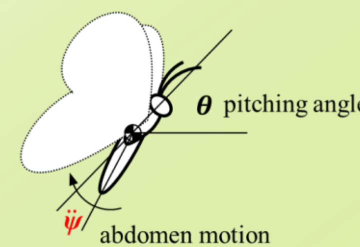
- Generate aerodynamic force
- Change inertia of a butterfly

→ Flight control method

Abdomen motion.







Tracking the flight kinematics of butterflies in experiment.

邱筠雅碩士論文，2020/07
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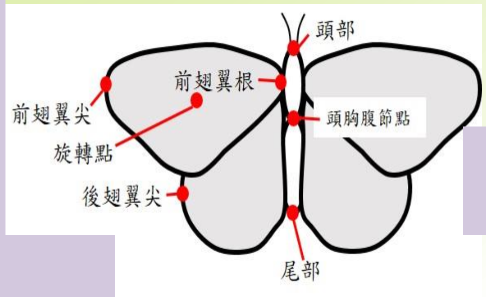
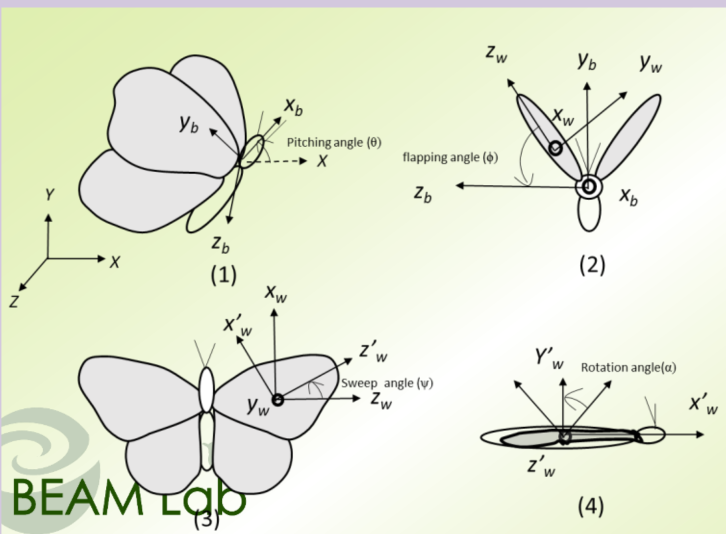
研究方法　建立運動函數

標記之特徵點



角度定義



標點結果

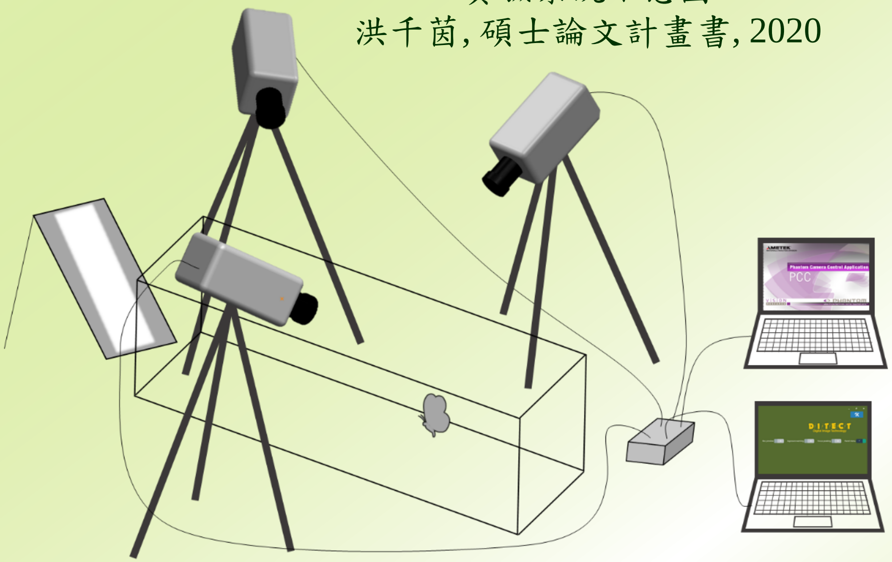
側視

俯視

邱筠雅碩士論文，2020/07
撓性與旋轉角於大白斑蝶及仿蝴蝶拍撲機構升力之影響

翼面變形效應觀測、驗證假說

實驗系統示意圖
洪千茵, 碩士論文計畫書, 2020



實驗系統實體圖

以六自由度荷重元測量升阻力示意圖

邱筠雅碩士論文，2020/07
撓性與旋轉角於大白斑蝶及仿蝴蝶拍撲機構升力之影響

尺寸 → 翅脈 → 薄膜 → 成品

$$\begin{cases} \bar{c} = \sqrt{\dfrac{f^{+}}{f}}\,\bar{c}^{+} \\ V = \sqrt{\dfrac{f}{f^{+}}}\,V^{+} \end{cases}$$

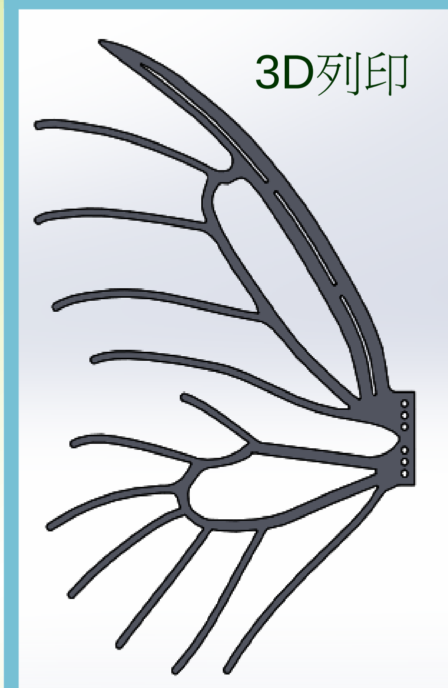
$\bar{c}^{+} = 42.81$ mm

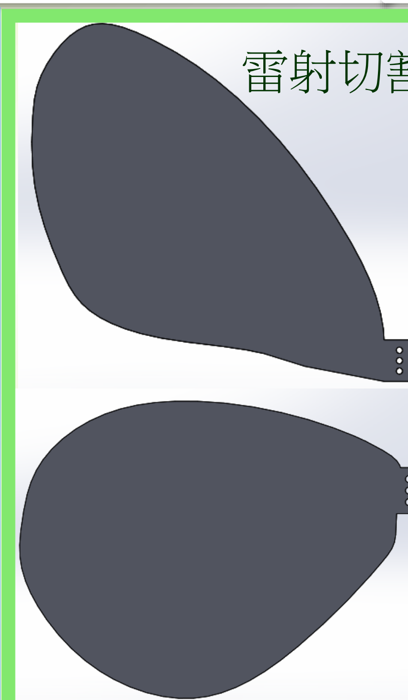
$f^{+} = 8.40$ Hz

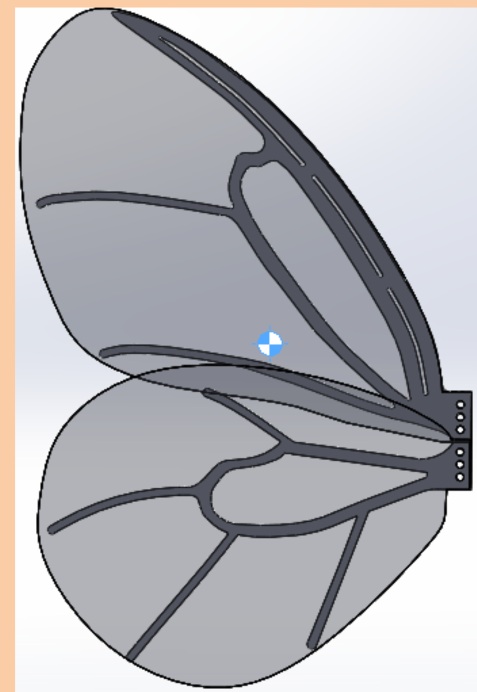
$f = 0.8$ Hz (設)

$AR = \dfrac{S}{\bar{c}} = 1.47$

S = 203.92 mm







邱筠雅碩士論文，2020/07
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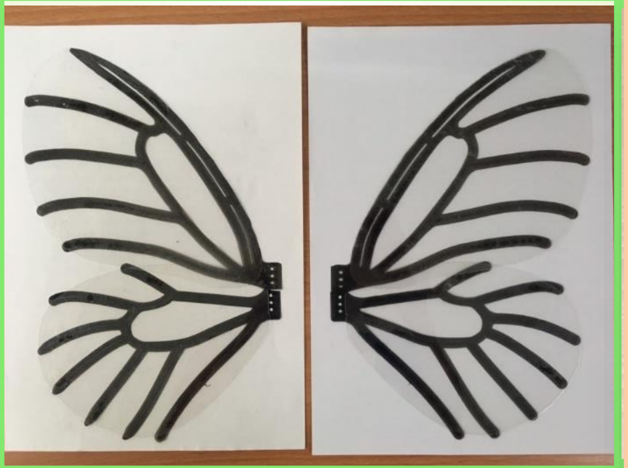
重量問題 → 剛性問題 → 第一代翅膀

翅脈：TPU 2 mm
薄膜：PC 0.125 mm
TPU密度：30%

翅脈：PLA 0.6 mm
薄膜：PET 0.075 mm
PLA密度：30%



翅脈：PLA 0.6 mm
薄膜：PET 0.075 mm
PLA密度：**90%**

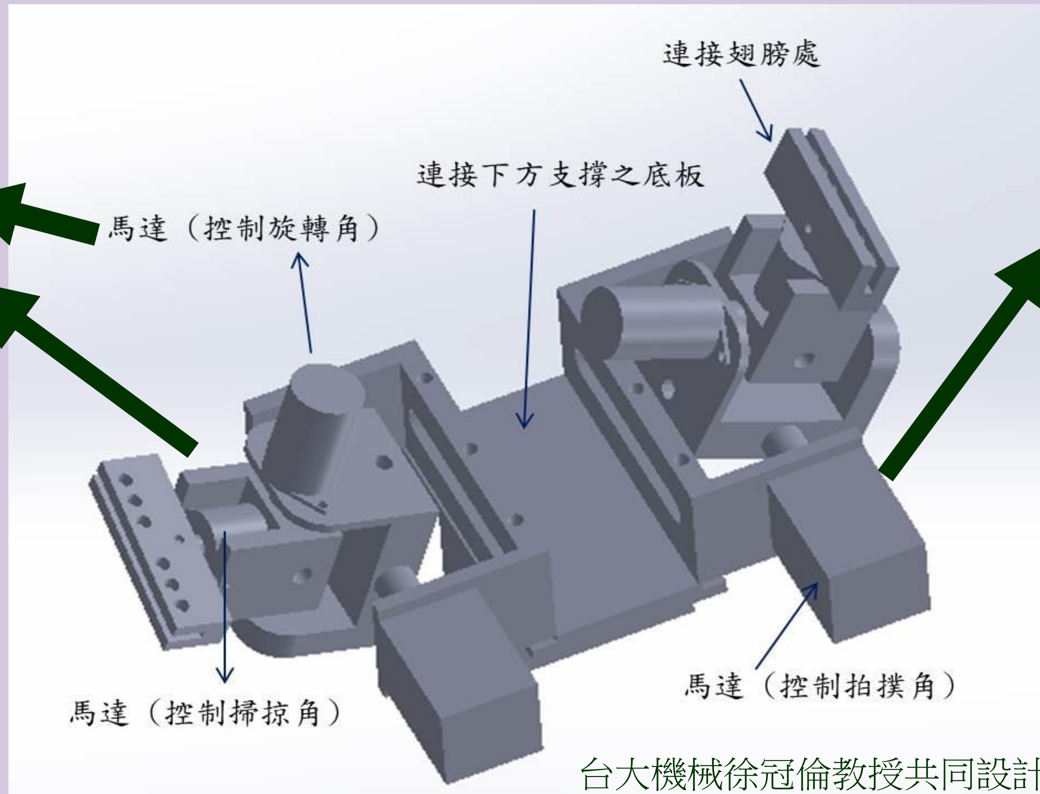
邱筠雅碩士論文，2020/07
撓性與旋轉角於大白斑蝶及仿蝴蝶拍撲機構升力之影響

研究方法　　機構設計

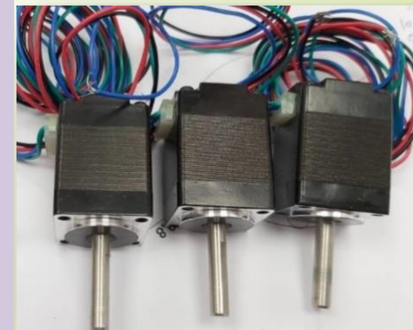
掃掠角
旋轉角

M10SP-XX45 (微太科技)	
減速比	1.0:93.5
扭矩	17 gf-cm

機構設計圖檔



拍撲角



TS3641N2E3 單軸步徑馬達	
減速比	1.0:21.5
扭矩	0.9 kgf-cm

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邱筠雅碩士論文，2020/07
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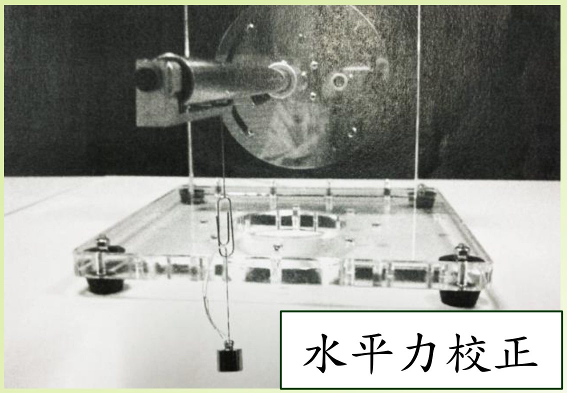
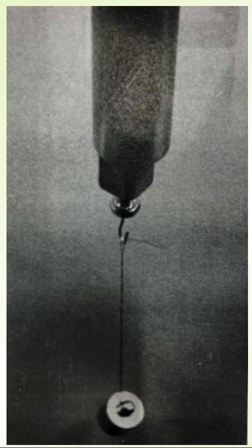
六分量平衡儀

校正重量：迴紋針重、500 mg、5 g、20 g、50 g、100 g

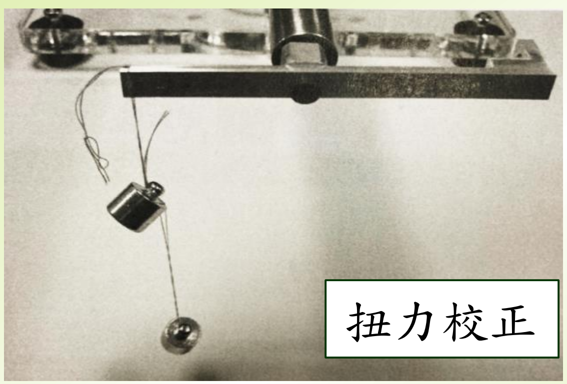
校正姿態



水平力校正

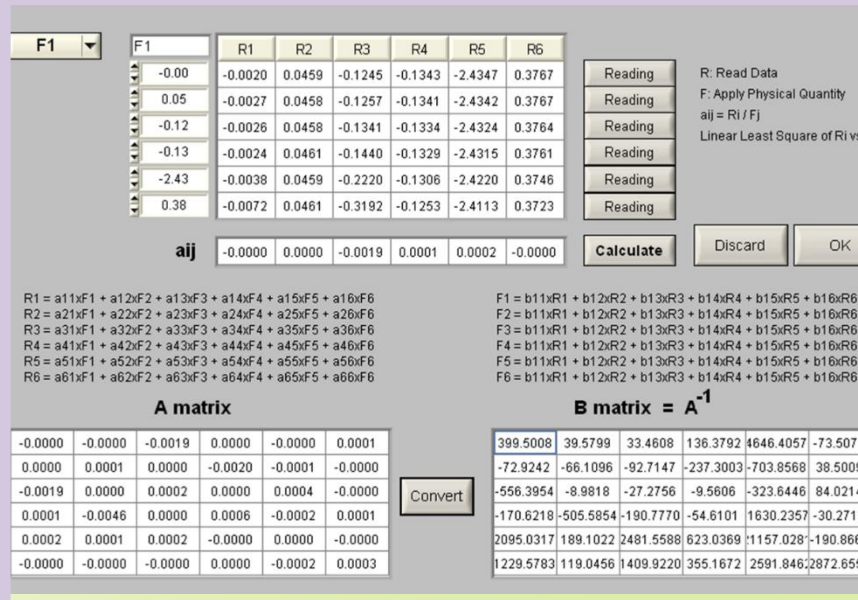


垂直力校正



扭力校正

校正畫面與其矩陣

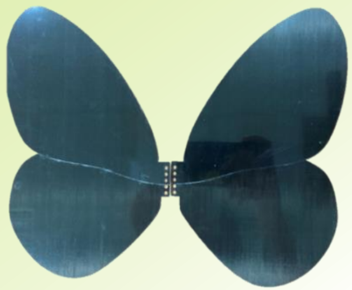


邱筠雅碩士論文，2020/07
撓性與旋轉角於大白斑蝶及仿蝴蝶拍撲機構升力之影響

結果與討論　翅膀撓性

$$\Pi_1 = \frac{D_s}{\rho U_{ref}^2 \bar{c}^3} = \frac{E h_s^3/(12(1-\nu^2))}{\rho V^2 \bar{c}^3}$$

撓性低
Carbon



適當撓性
PLA

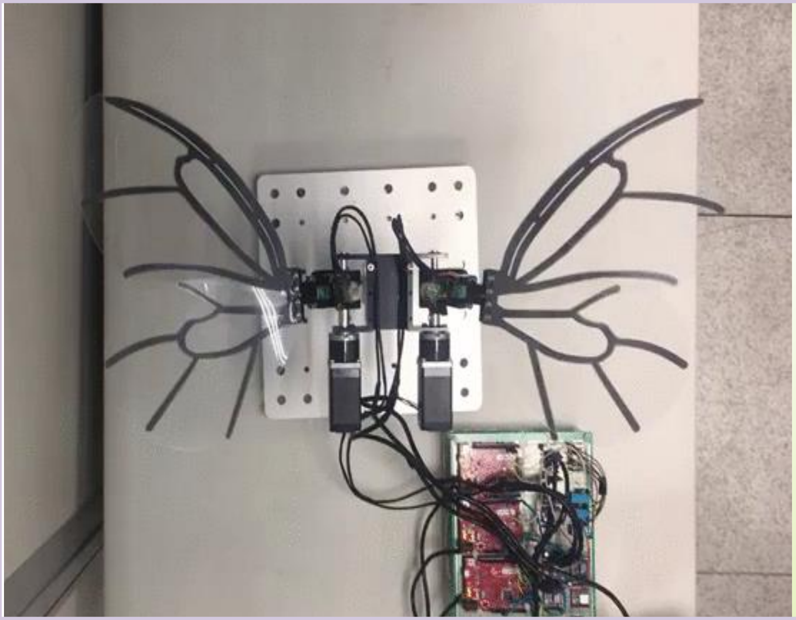
撓性程度高
PETG

		Carbon	PLA	PETG
總重		19.8625 g	9.0844 g	17.8671 g
厚度		0.3 mm	0.25 mm	0.3 mm
拉伸模數 (Tensile modulus, E)		145.4 GPa	4.5 GPa	2.01 GPa
蒲松比(Poisson's ratio,*v*)		0.3	0.33	0.44
彎曲剛度(flexible rigidity, *D*)		3.60×10^{-1}	6.52×10^{-4}	4.59×10^{-4}
翼尖速度	無旋轉	515.0 mm/s	510.6 mm/s	545.4 mm/s
	有旋轉	525.7 mm/s	611.5 mm/s	525.7 mm/s
無因次撓性參數 (Π_1)	無旋轉	603.41	11.28	8.39
	有旋轉	579.09	7.83	7.07

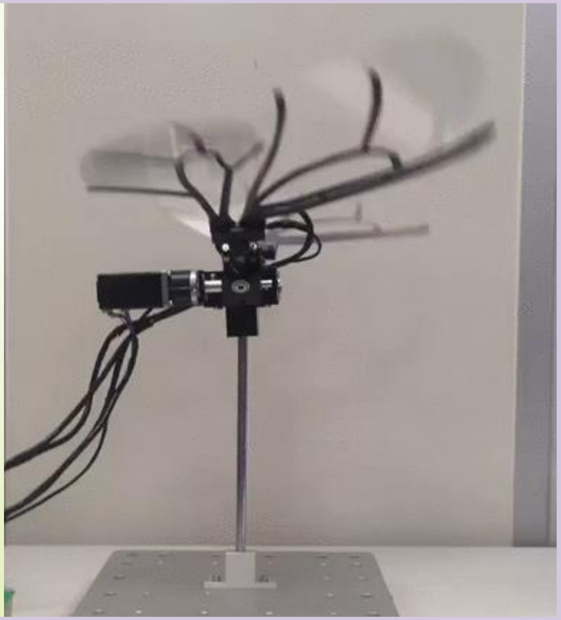
邱筠雅碩士論文，2020/07
撓性與旋轉角於大白斑蝶及仿蝴蝶拍撲機構升力之影響

結果與討論　機構成品與測試

拍撲機構成品



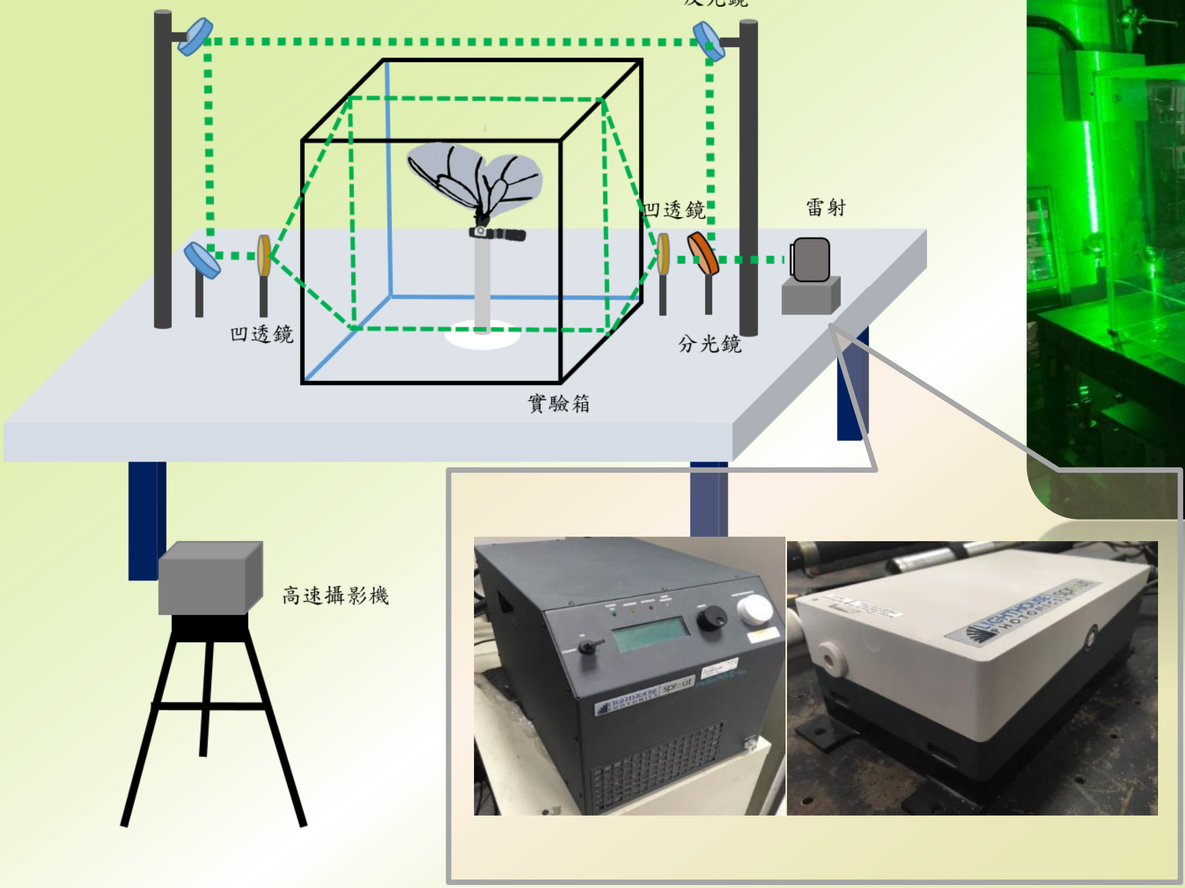
俯視

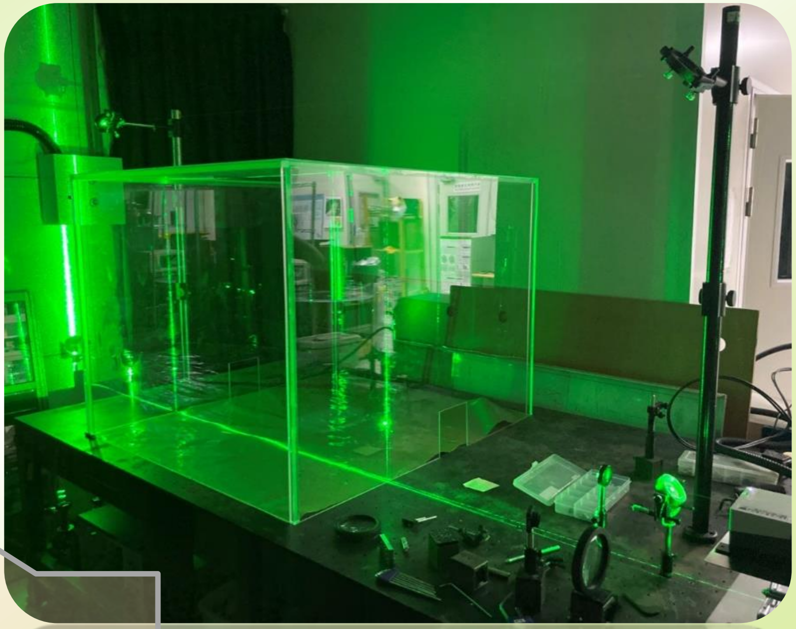


側視

邱筠雅碩士論文，2020/07
撓性與旋轉角於大白斑蝶及仿蝴蝶拍撲機構升力之影響

流場觀測方法 粒子影像測速法





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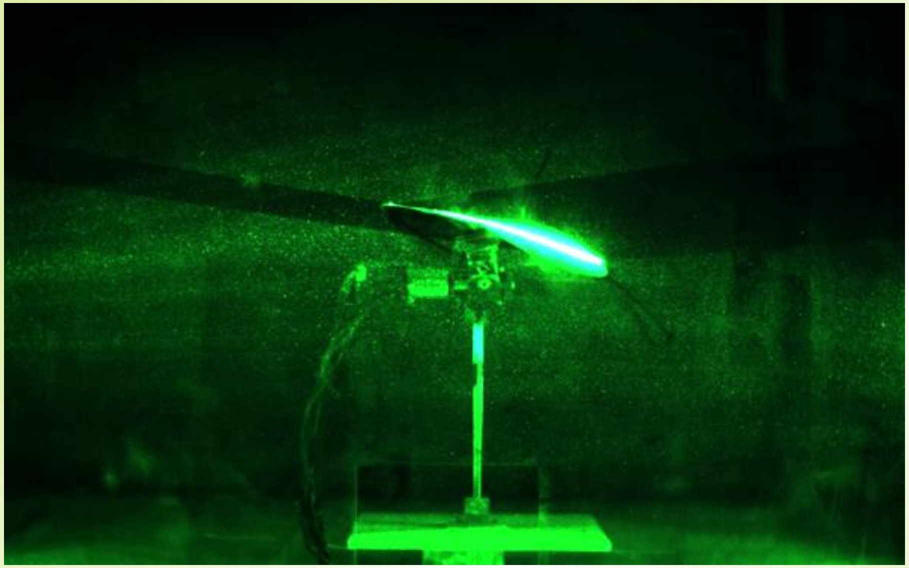
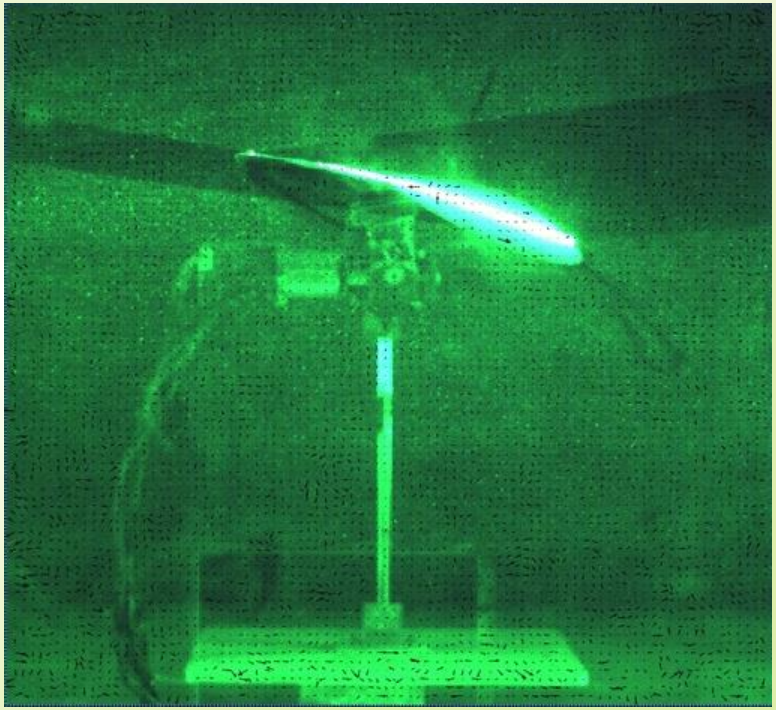
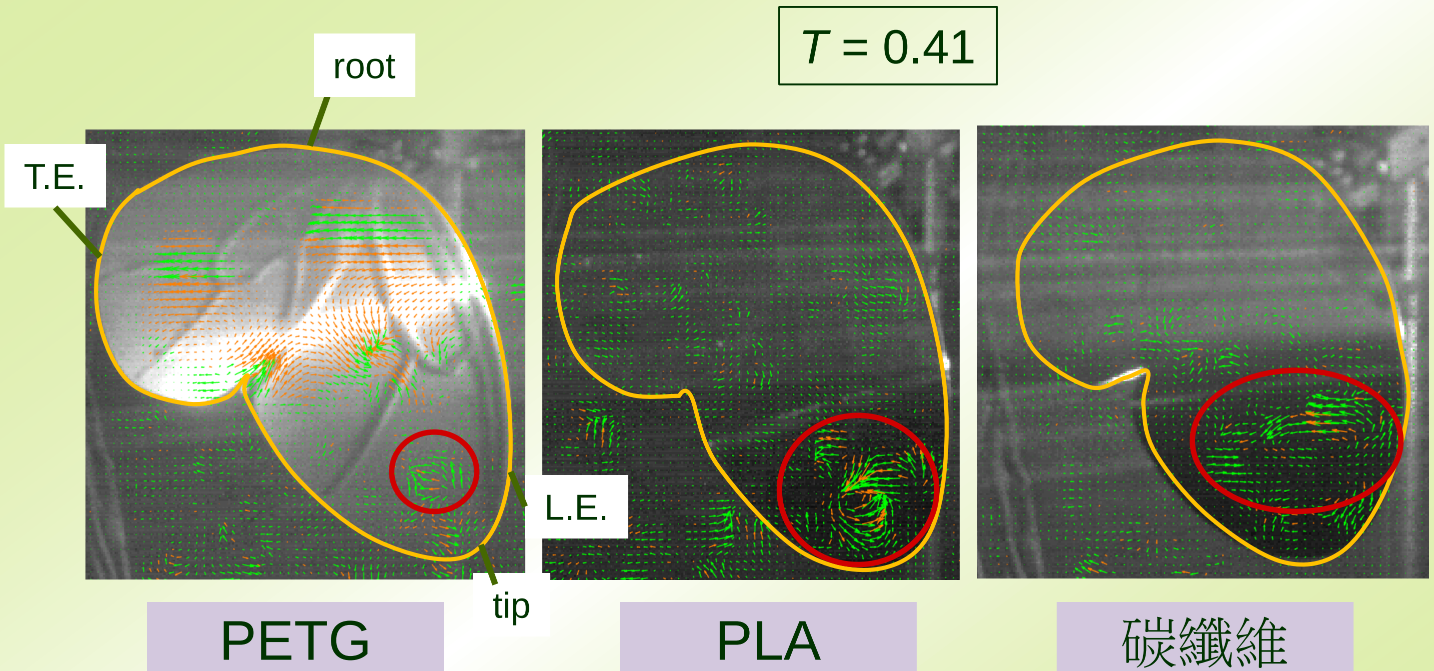
結果與討論　流場可視化 vs 飛行動態





台大機械 洪千茵 *et al.* 拍攝及分析, 2020/10

結果與討論　流場結構可視化



剛性程度　小　中　大

邱筠雅碩士論文，2020/07
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結論...進行式

觀察分析 大白斑蝶 → **設計 仿蝴蝶機構** → **分析 飛行策略**

建立動作函數
分析旋轉與拍撲相位差

撓性翅膀 + 主動旋轉
(領先相位 約0.03週期)

以三個馬達獨立
控制翅膀三自由度

仿真實蝴蝶翅脈製作
三種不同剛性程度翅膀

控制旋轉角馬達相位
(1) 無旋轉
(2) 對稱旋轉
(3) 領先旋轉
配合不同剛性程度翅膀

力	流場	功耗率
六分量平衡儀	PIV	

以主動之對稱旋轉動作，配合適當撓性之翅膀，可以獲得最大的升力提升及較少的能量消耗。

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日本HONDA機器人 ASIMO

端茶
接待
家用


To the future...

待續　　Q & A…

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