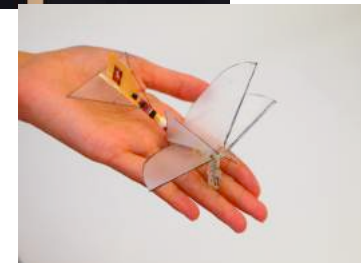
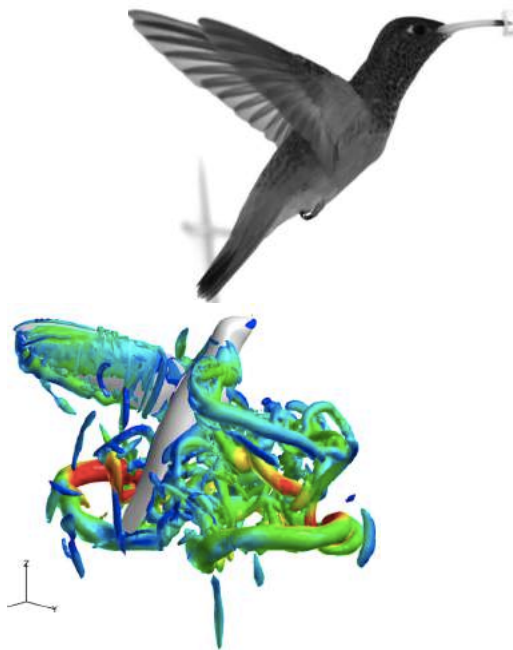


# Lessen from Insects: Robustness Strategies for Bio-inspired Flying Robots

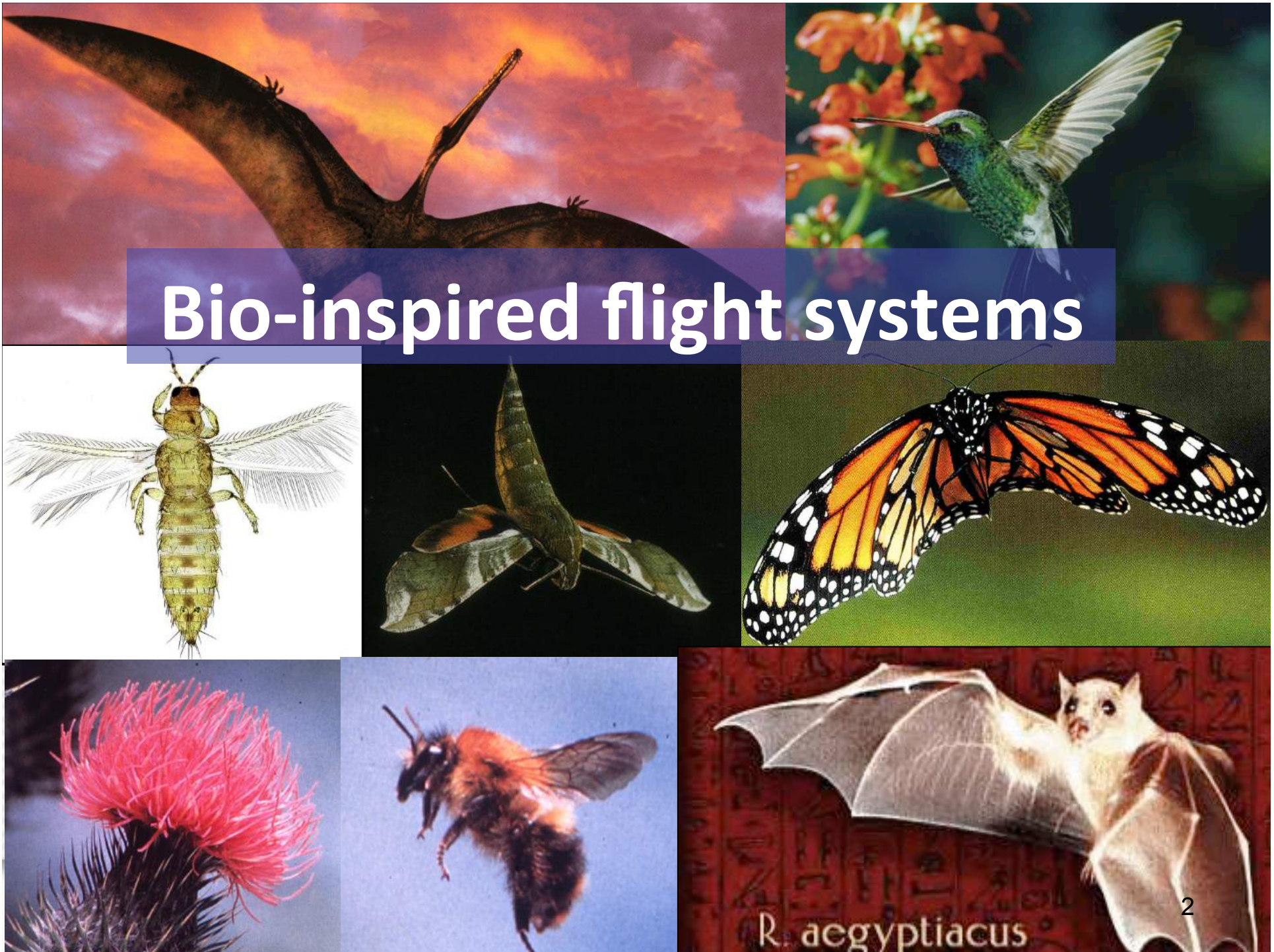


**Hao LIU**

**Graduate School of Engineering  
Chiba University, Japan**



# Bio-inspired flight systems



R. aegyptiacus

Bio-inspired flight system presents an exciting venture in biomimetics, integrating many different aspects.

***Hawkmoth in hovering (Liu lab)***

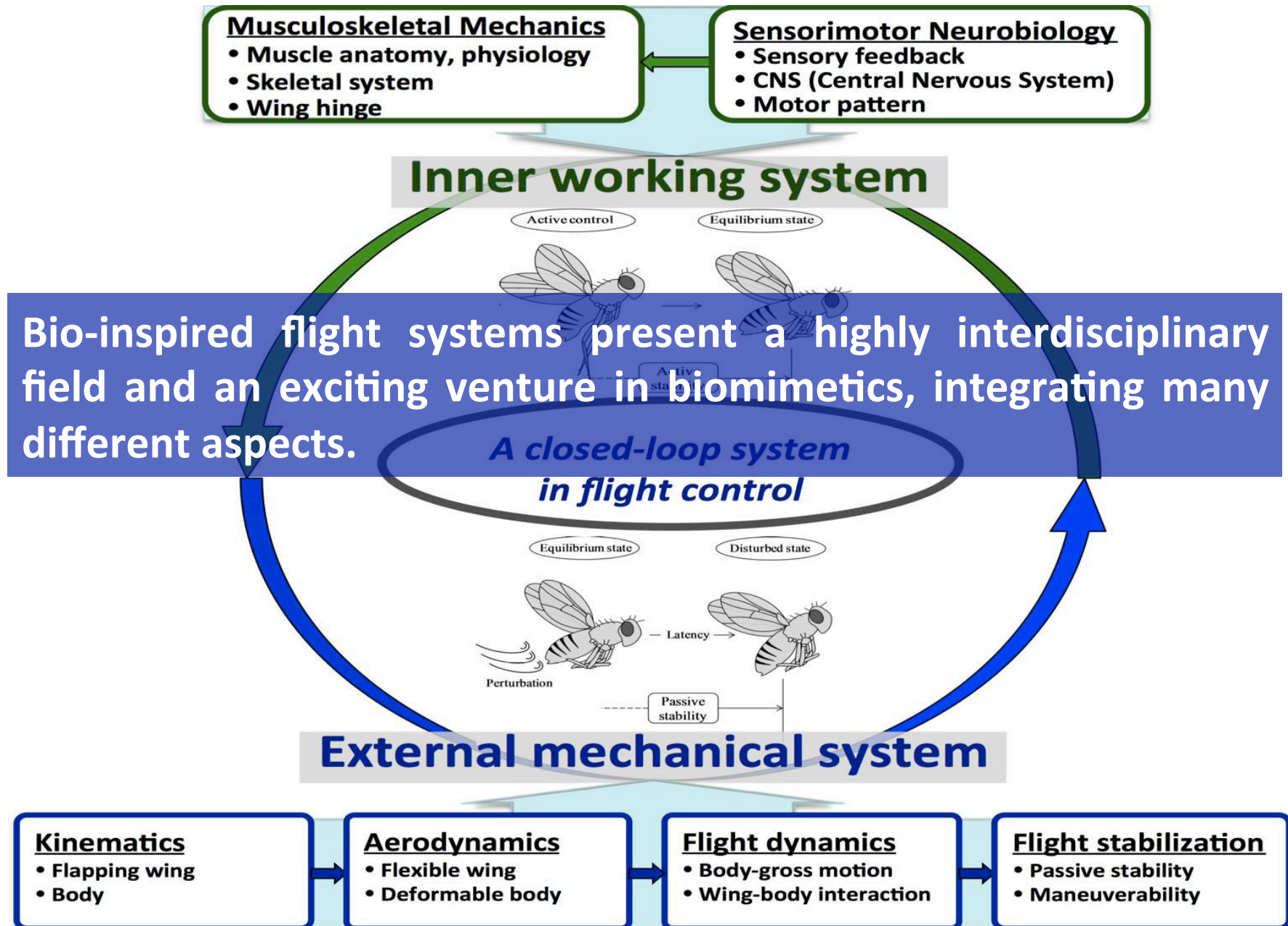


***Hummingbird in hovering (Liu lab)***

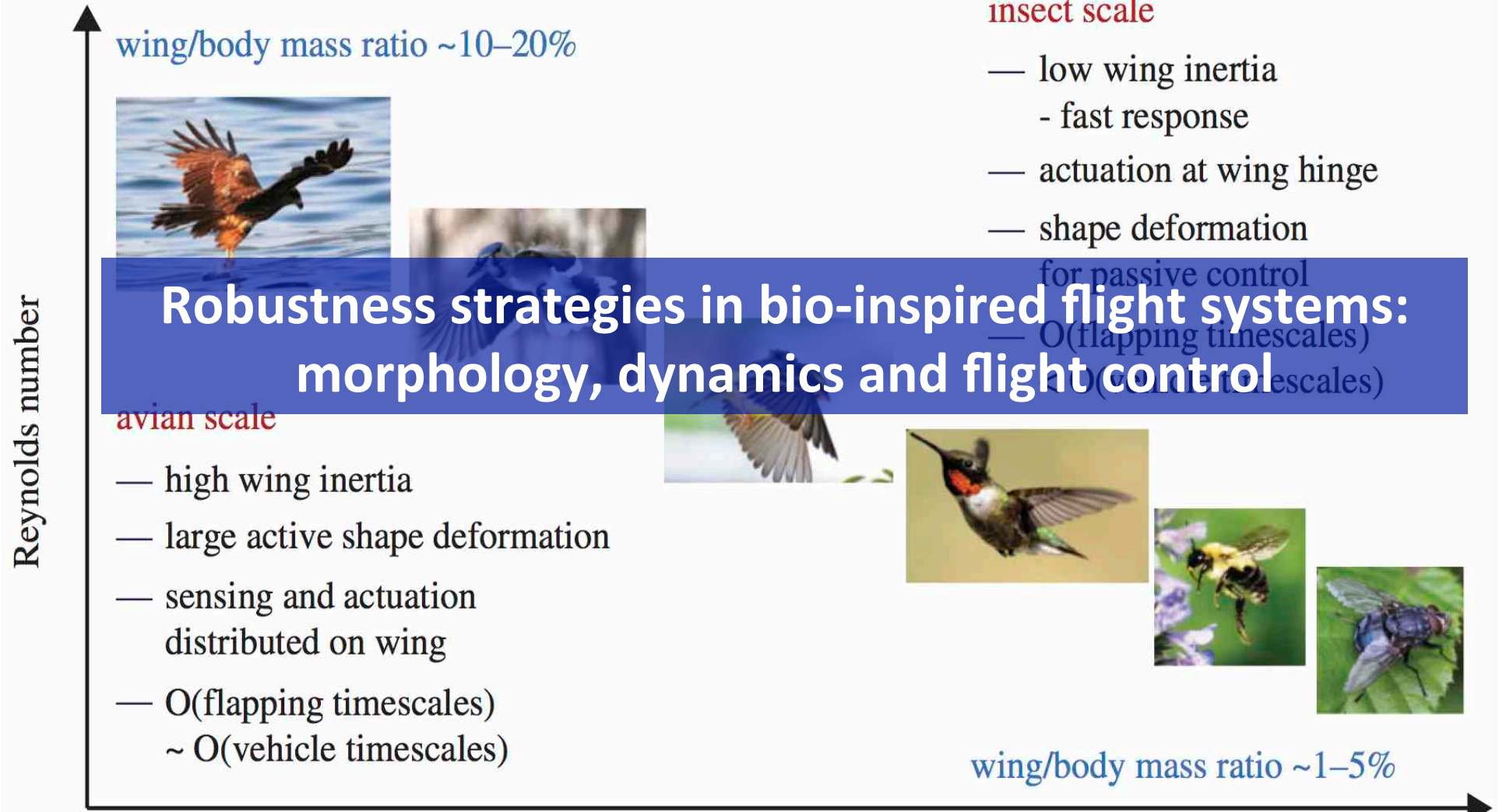


Bio-inspired flapping-wing system presents a highly nonlinear multi-mechanical problem integrating low Reynolds number unsteady aerodynamics, structural mechanics of wing and body, multi-body flight dynamics and feedback flight control.

# How do insects fly?



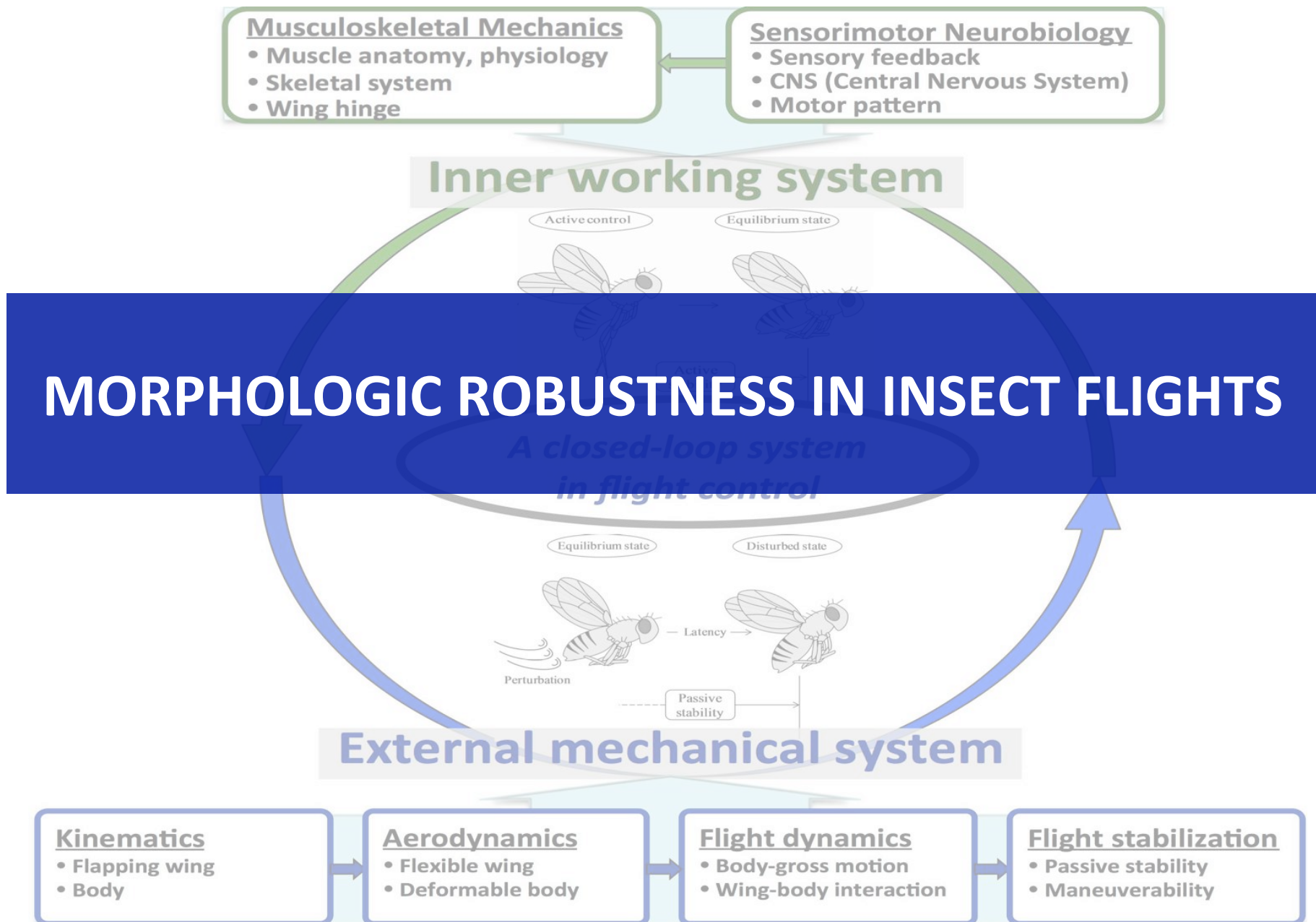
# Robustness and Diversity in Biological Flights



**Robustness strategies in bio-inspired flight systems:  
morphology, dynamics and flight control**

Shyy, Liu et al *Philosophical Transactions of the Royal Society A* 2016

*R. aegyptiacus*

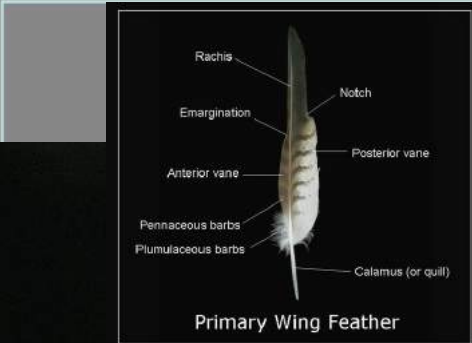
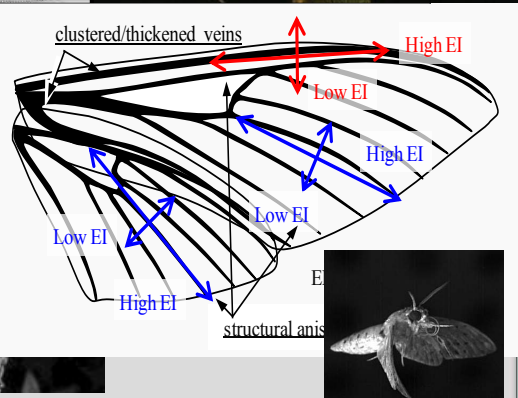
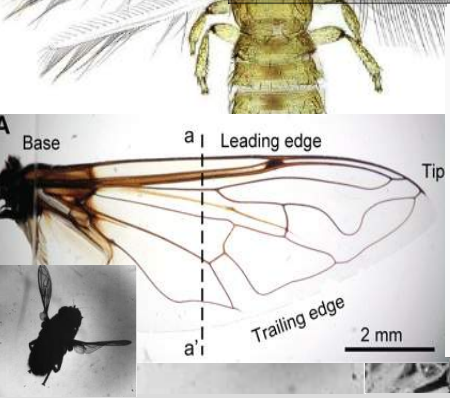
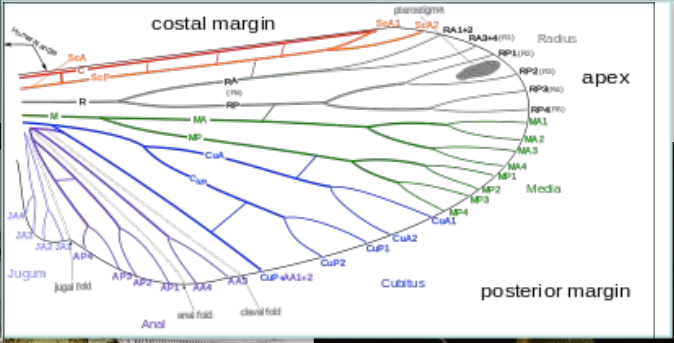


# Wing morphing-based aerodynamics vs size cross insects and birds

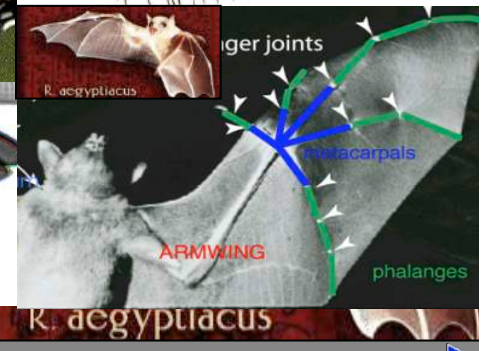
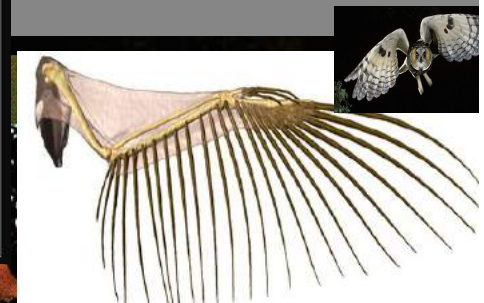
## Scaling macroscopic principles for wing deformation

### And flexible wing aerodynamics

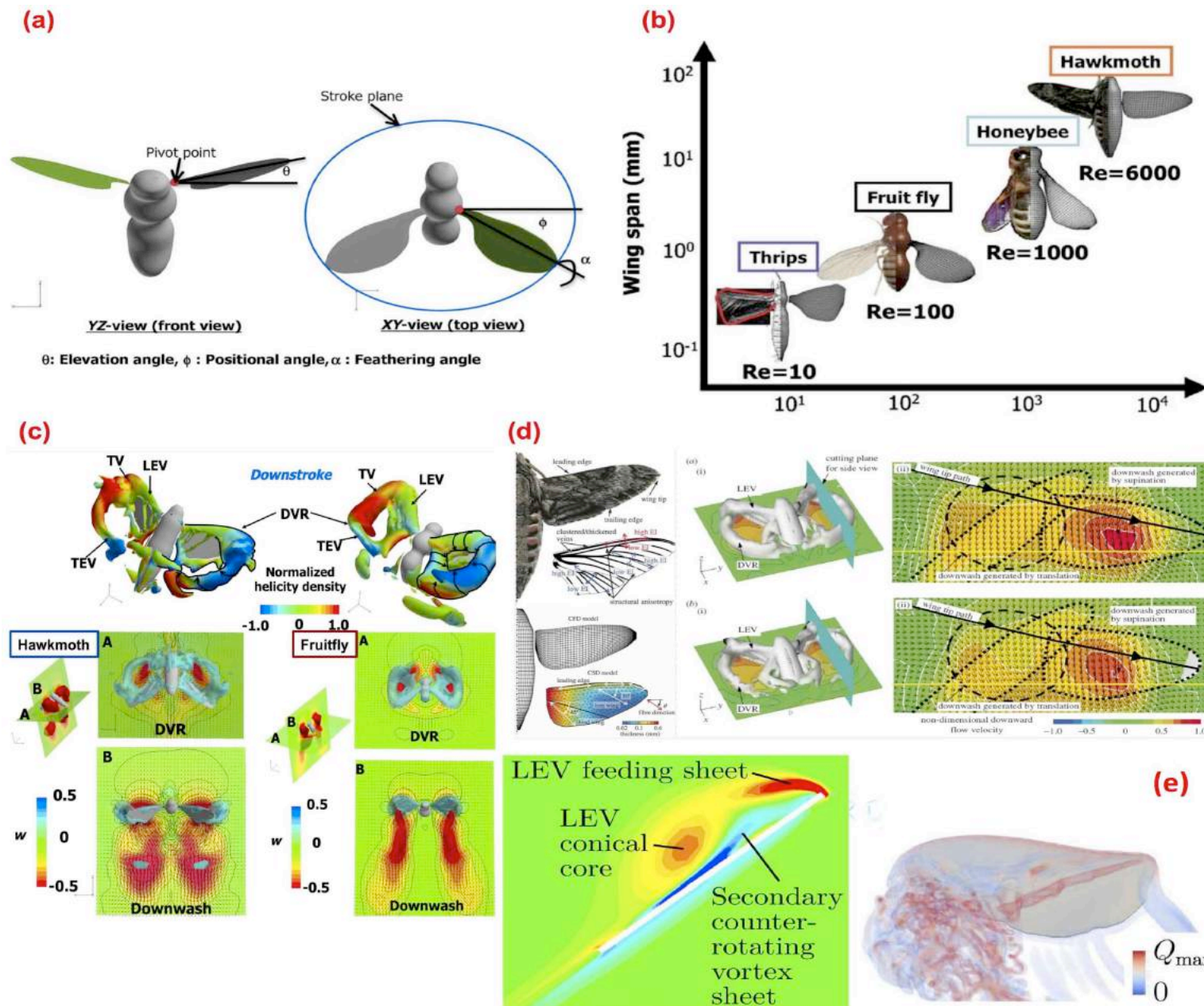
#### Insects



#### Bat and Birds



It is still unclear how the three-dimensional and passive change of wing kinematics owing to inherent wing flexibility contributes differently or similarly to unsteady aerodynamics and energetics in flapping flights of insects, bat & birds.

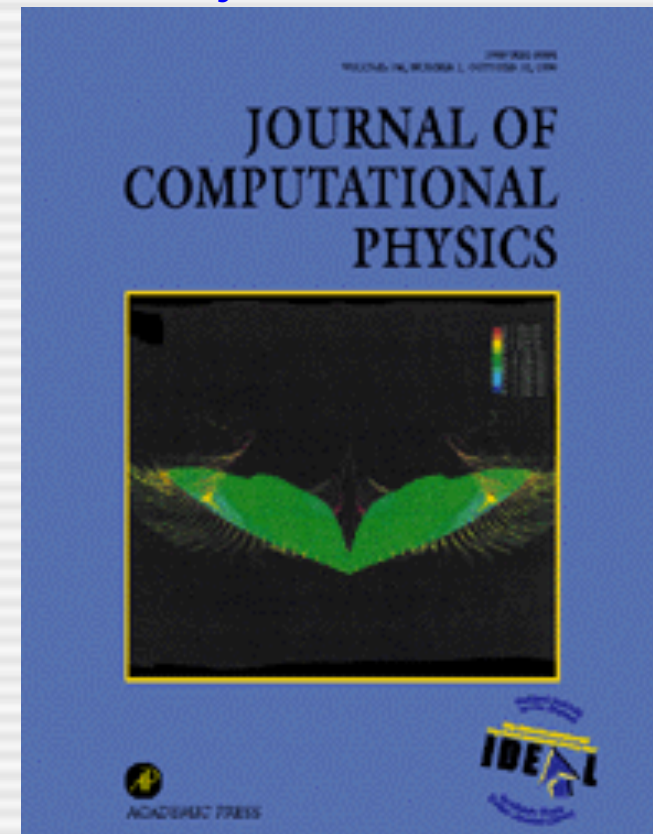
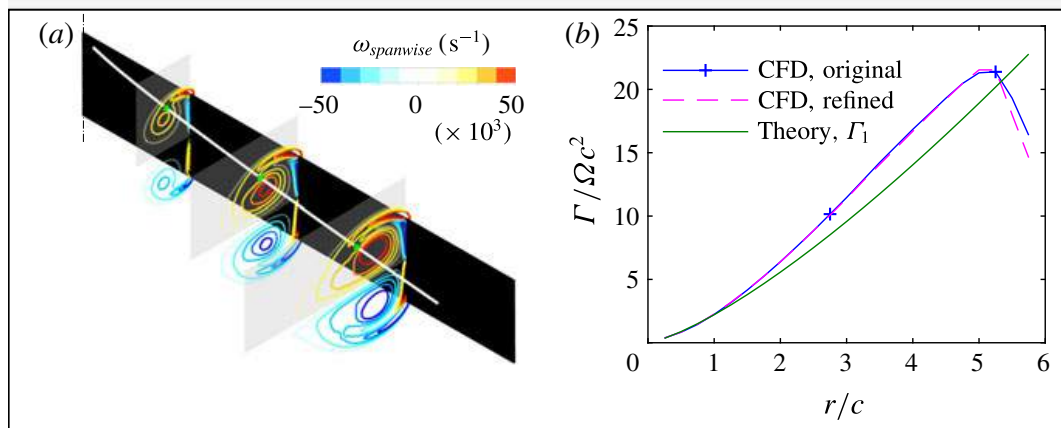
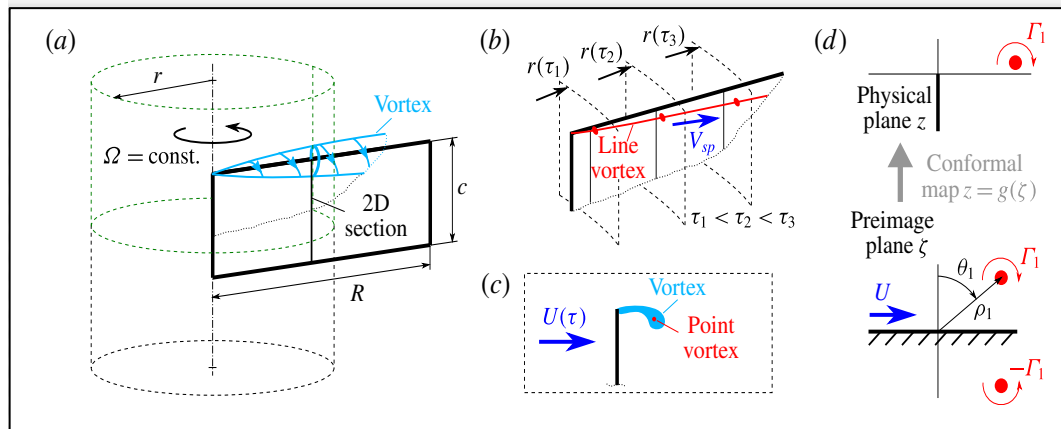


(a) Wing kinematics. (b) Wing morphologies. (c) Near-and far-field vortex dynamics in fruitfly and hawkmoth hovering. (d) Flexible wings aerodynamics in hovering hawkmoth. (e) Vortex dynamics around a revolving bumblebee wing.

# Robustness in wing morphology

**Flapping and revolving wings can produce attached leading-edge vortices** when the angle of attack is large. A low-order model is proposed for the edge vortices that develop on a revolving plate at 90 angle of attack, which is the simplest limiting case, yet shows remarkable similarity with the generally known leading-edge vortices.

Chen, Kolomenskiy, Liu. *J. Fluid Mech.* 2017



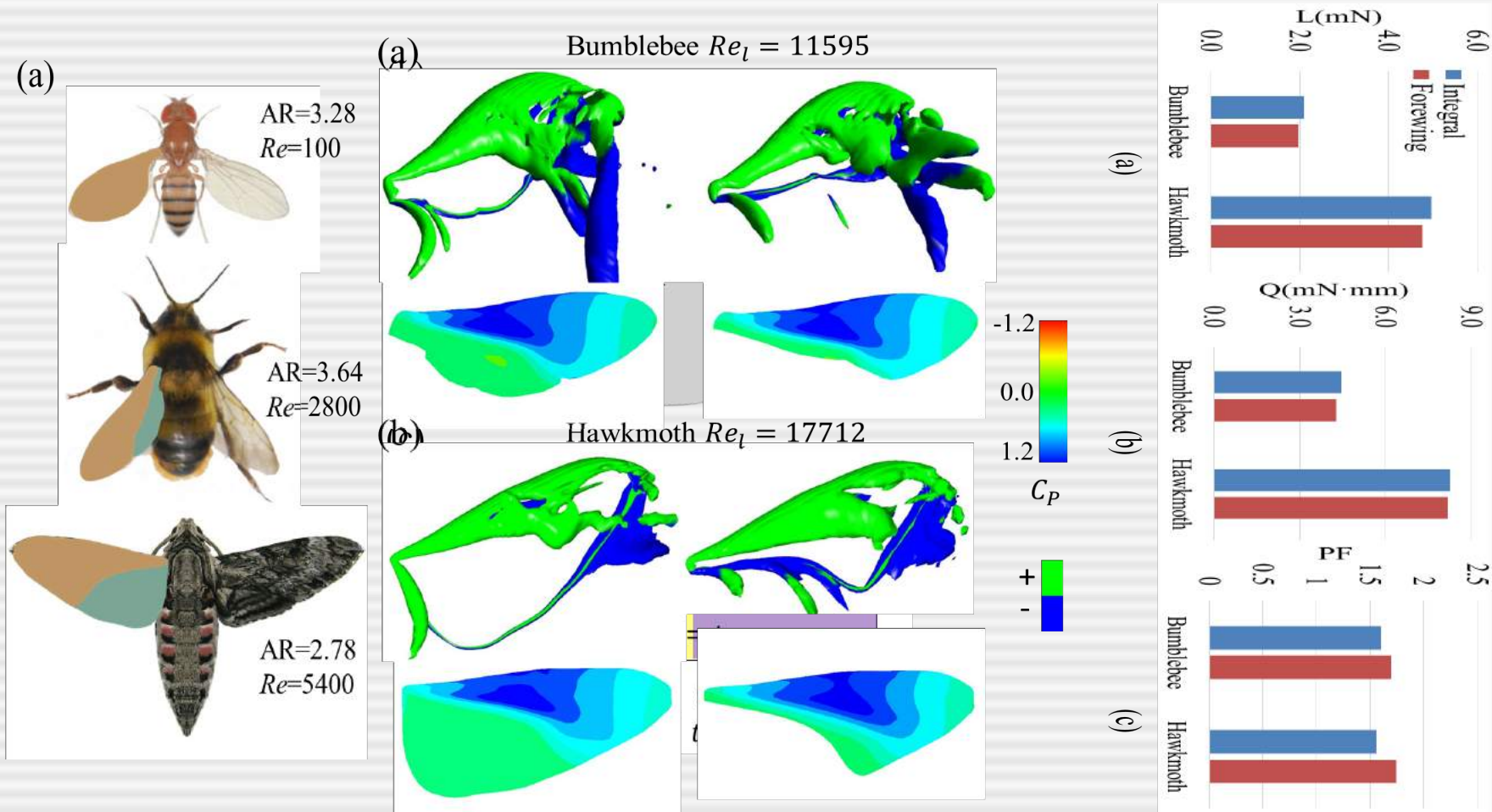
Liu et al *J. Comp. Phys, J. Exp. Biol* 1998



国立大学法人 千葉大学  
National University Corporation  
Chiba University

# Robustness in wing morphology

Forewing morphology plays a dominate role in achieving low-Reynolds number aerodynamic performance in natural flyers as well as in revolving and/or flapping micro air vehicles. *Chen, Kolomenskiy, Liu. Bioinspir. Biomim. 2017*



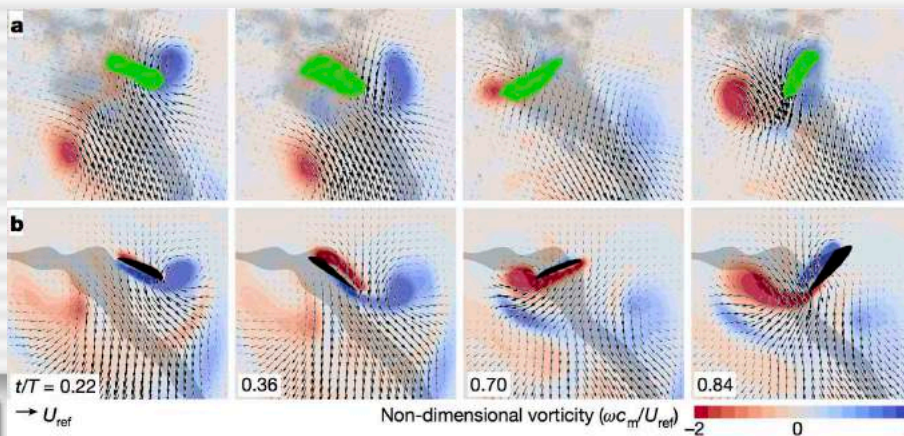
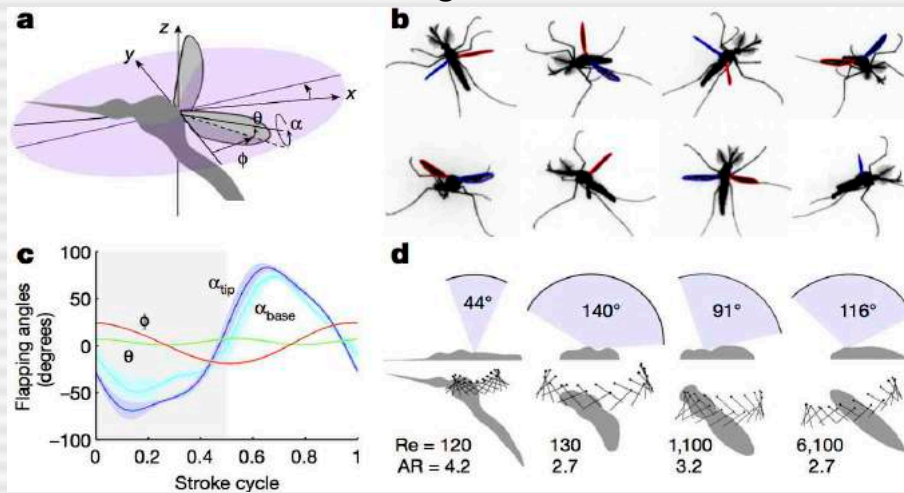
# Robustness in wing morphology

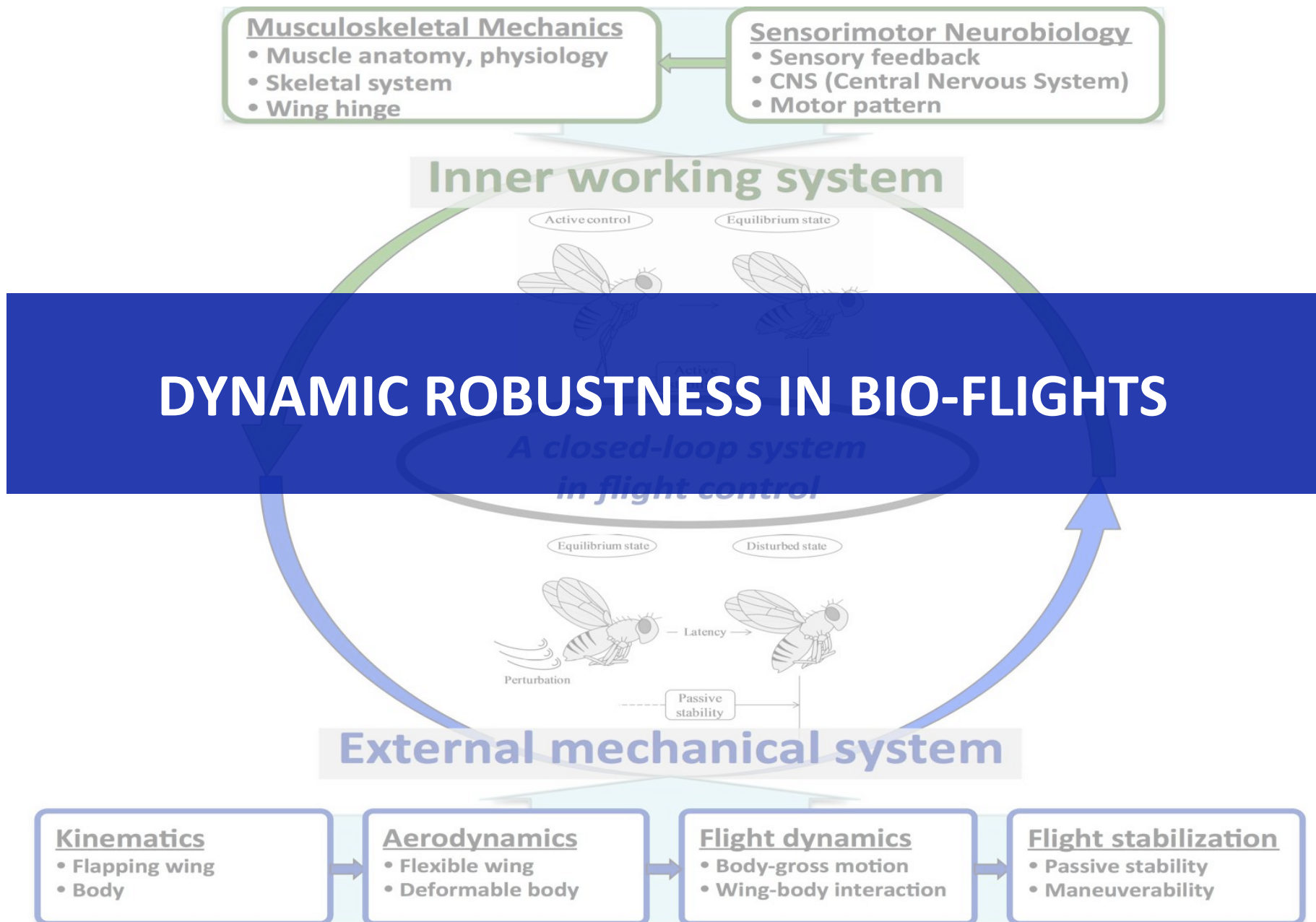
## “Smart wing rotation and trailing-edge vortices enable high frequency mosquito flight”

Although mosquitoes use familiar separated flow patterns, much of the aerodynamic force that supports their weight is generated in a manner unlike any previously described for a flying animal.

*There are three key features: leading edge vortices (a well-known mechanism that appears to be almost ubiquitous in insect flight), trailing-edge vortices caused by a form of wake capture at stroke reversal, and rotational drag.*

*Bumprehy, Nakata et al Nature. 2017*



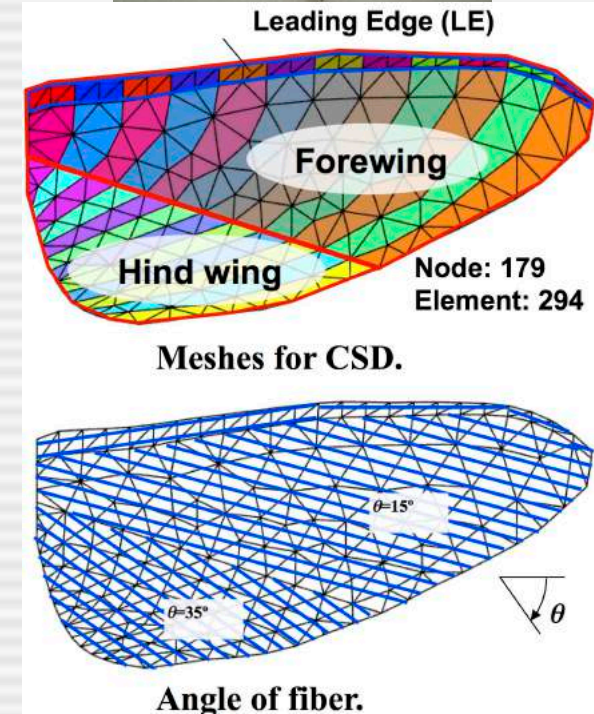
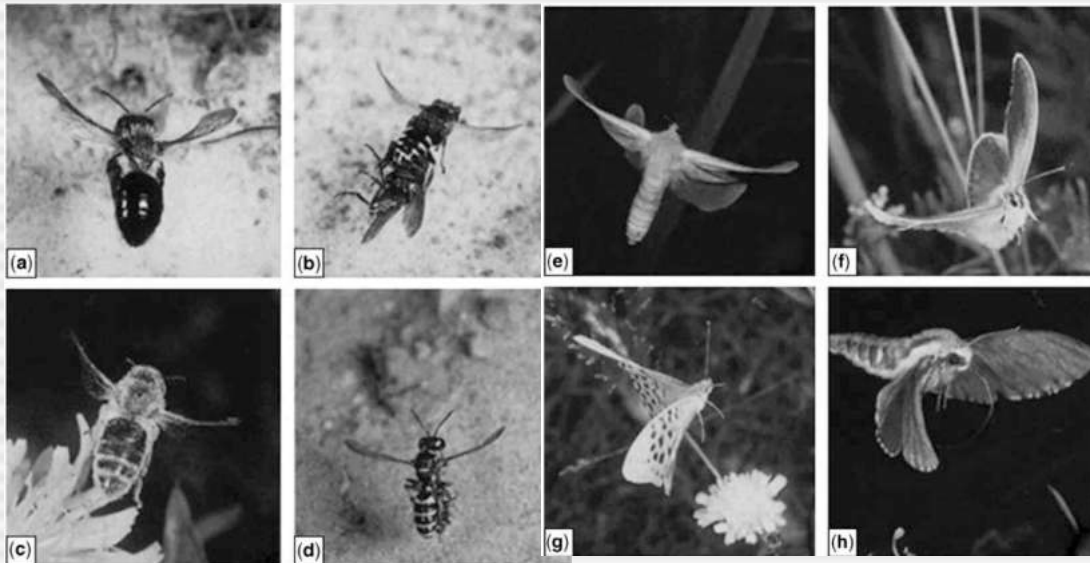




# Robustness in wing deformation

Passive deformation owing to wing flexibility in flapping flight is of robustness and capable of enhancing aerodynamic performance and flight stability.

Flying animals typically have *flexible wings* to adapt the flow environment.

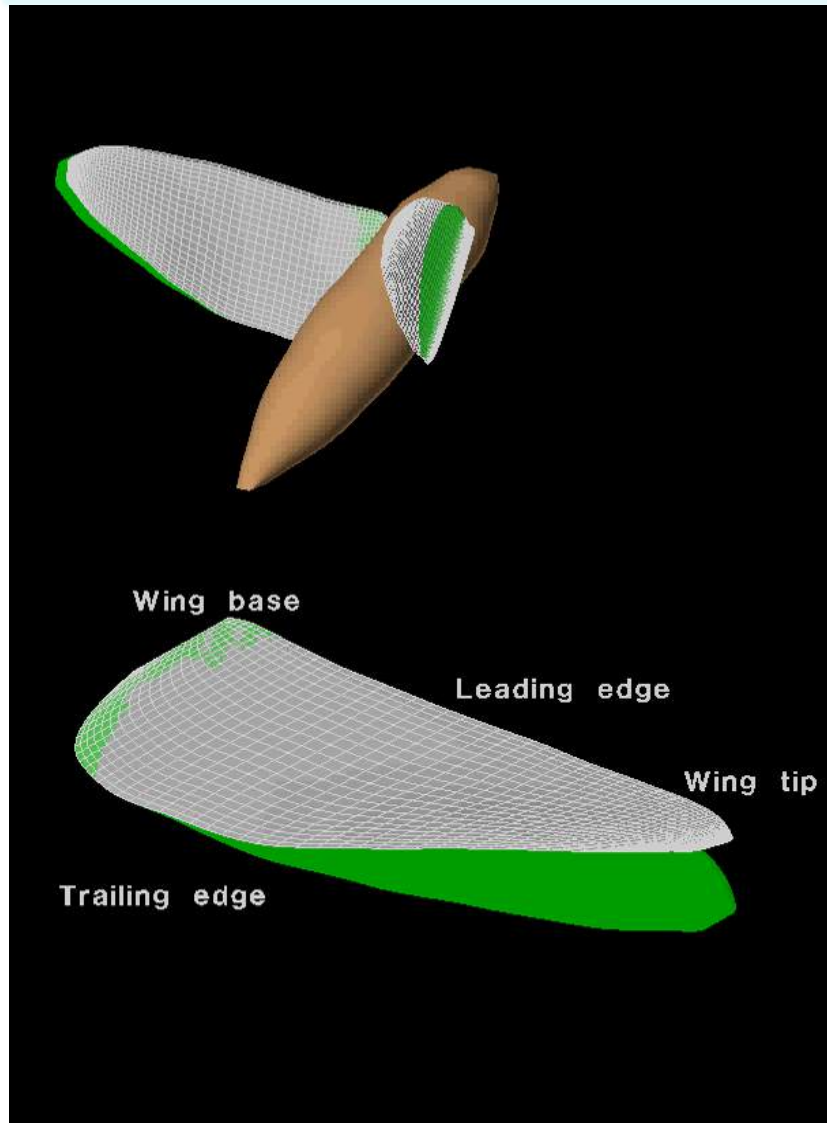


**A Fluid-Structure Interaction (FSI)  
of hawkmoth flapping wings**

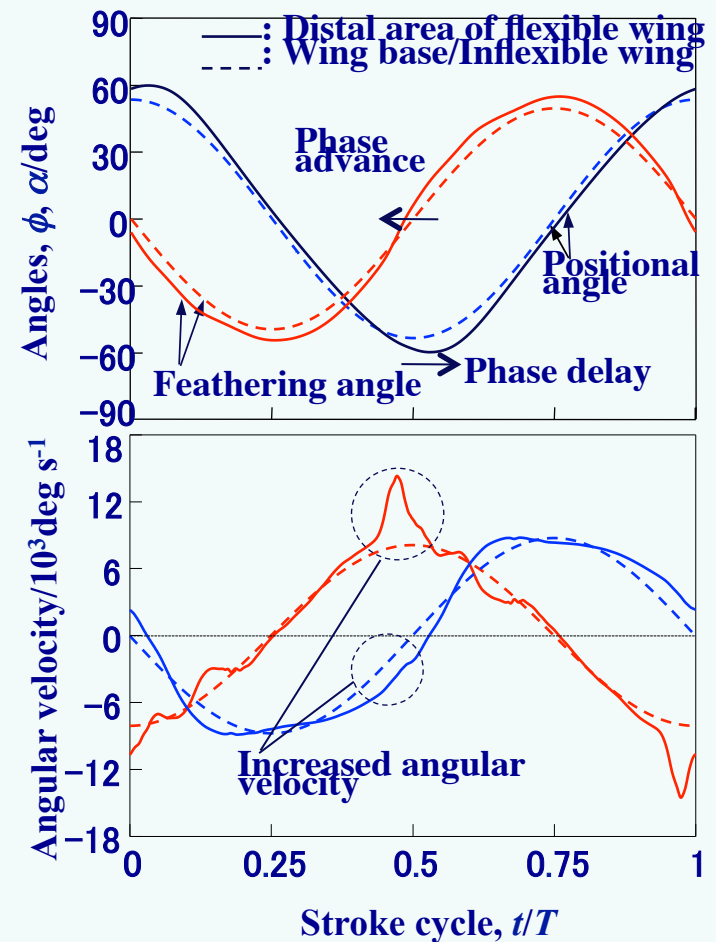
T. Nakata & H. Liu (*JCP*, 2011; *Proc R. Soc B*, 2011)



# Flexible wing aerodynamics (FSI)

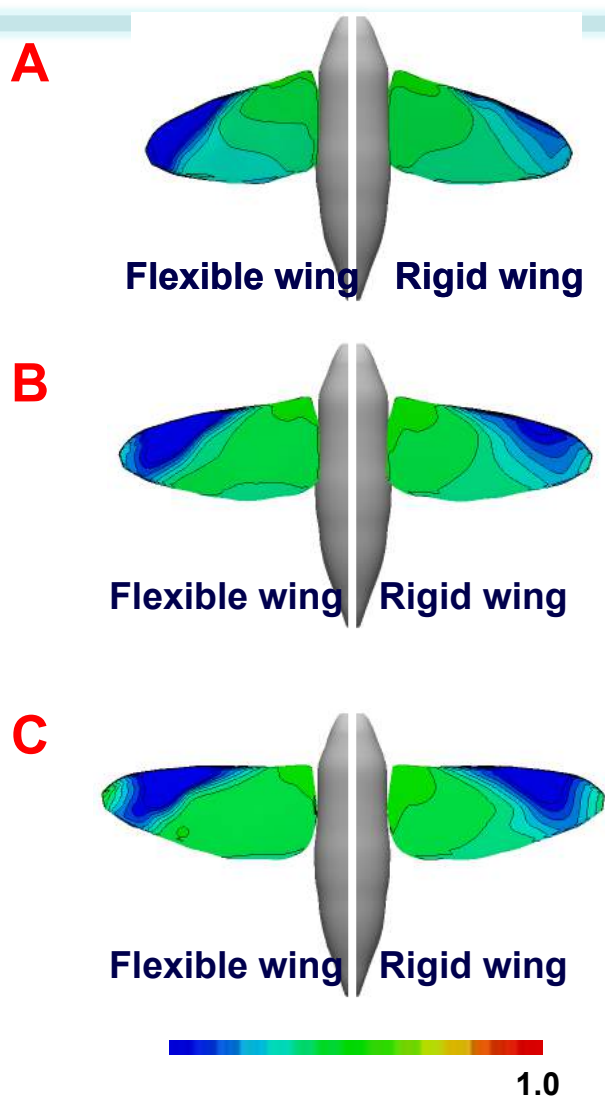


## Advanced rotation mechanism



Flapping and feathering angles of distal area of flexible wing and the angular velocities.

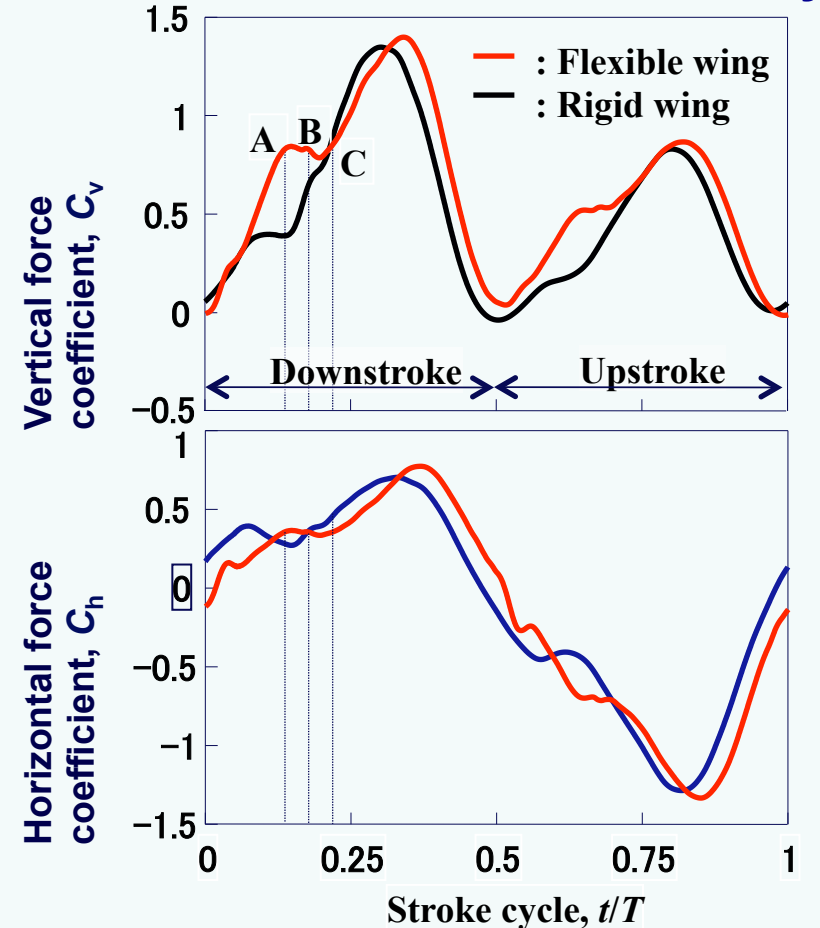
# Flexible wing aerodynamics (FSI)



Pressure(non-dimensional)

20% increase in average vertical force

13% increase in efficiency

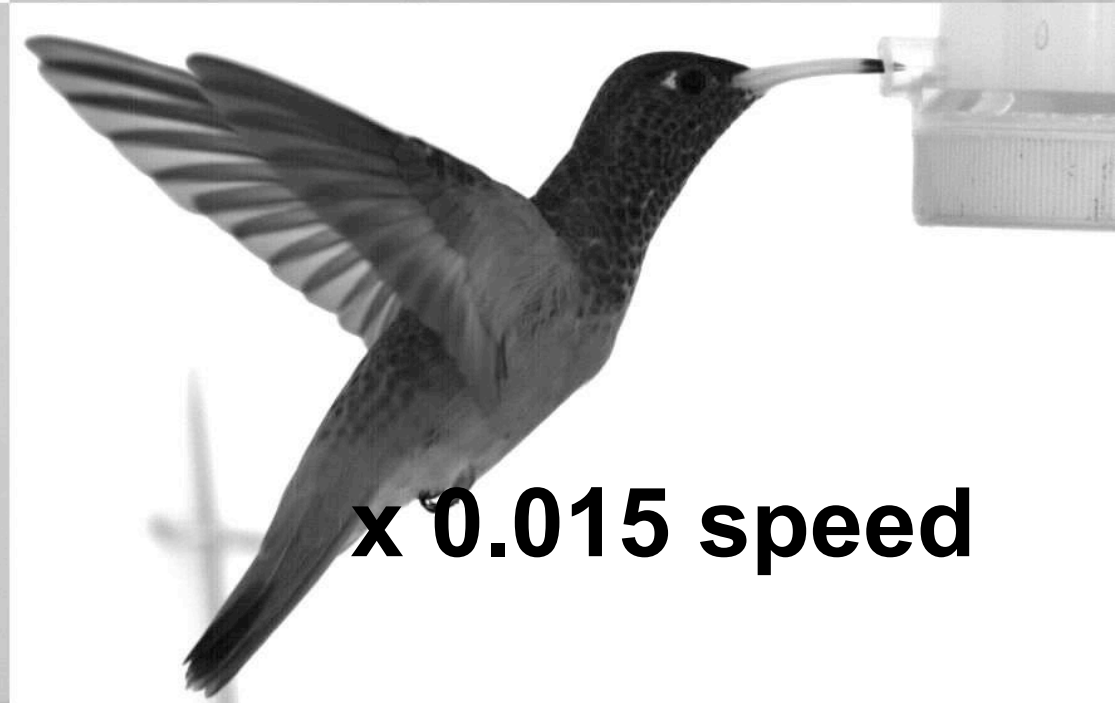


Time-courses of vertical and horizontal force coefficient generated by flexible and rigid wing.

T. Nakata & H. Liu (*JCP*, 2011; *Proc R. Soc. B*, 2011)<sup>16</sup>

**1<sup>st</sup> realistic CFD model with flexible wings revealed importance of wing deformation in hummingbird hovering.**

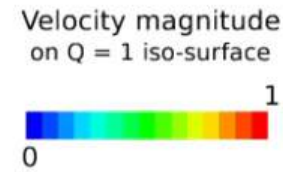
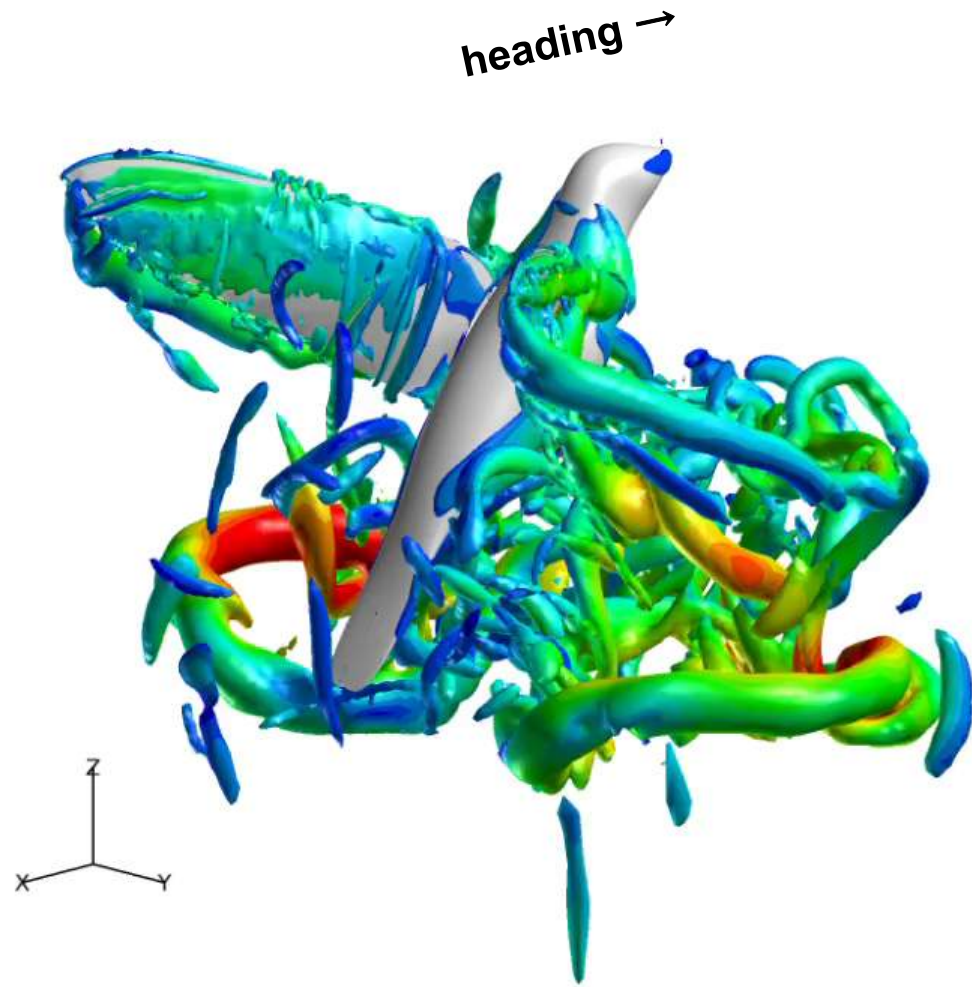
*(Maeda, Liu et al The Royal Society Open Science 2017)*



**x 0.015 speed**

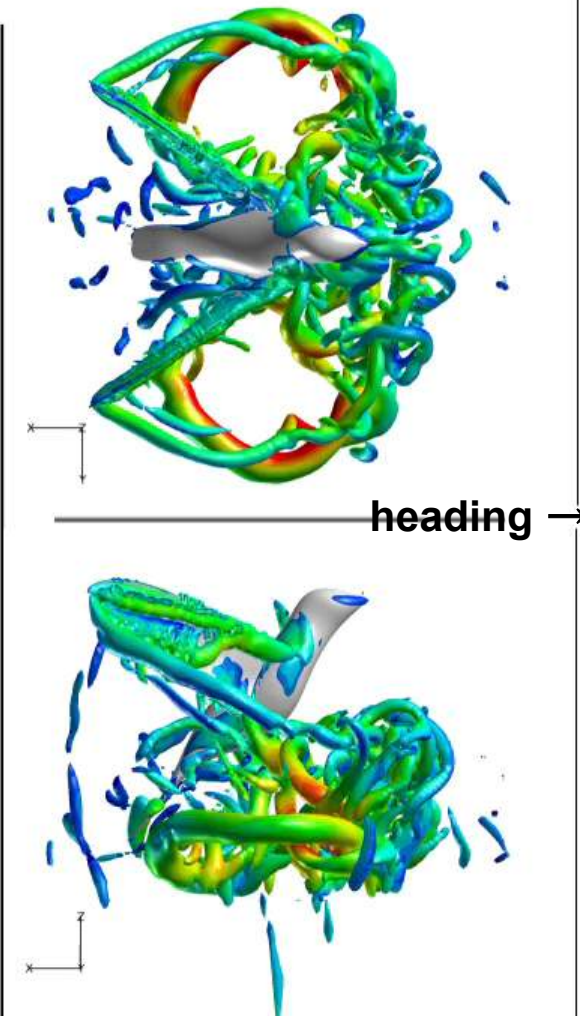
# Far wake

heading →  
top view



$t/T = 4.00$

slant view (from right, behind)



lateral (right) view

*In preparation, 2018*



# Cycle-averaged aerodynamic force, Power, Efficiency



All the values are time-averaged (2 to 3 cycle) and for the respective right wing.

**Hawkmoth**  
*Agrius convolvuli*

**Hummingbird**  
*Amazilia amazilia*

## Morphing (flexible) models

### Aerodynamics:

Wing flexibility in hovering flights of hawkmoth and hummingbird can create larger aerodynamic forces and achieve better aerodynamic efficiencies.

## Flat (rigid) models

### Implication for flapping MAV design:

Bio-inspired wing kinematics and deformation are more important rather than wing structure (vein, membrane, musculature).

$(F_v/P_{morphing}) / (F_v/P_{flat})$  15.4 % ↑

14.3 % ↑

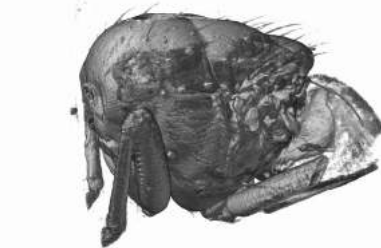
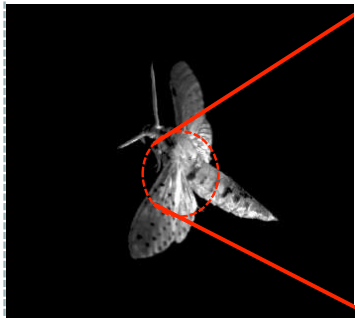
In preparation, 2018



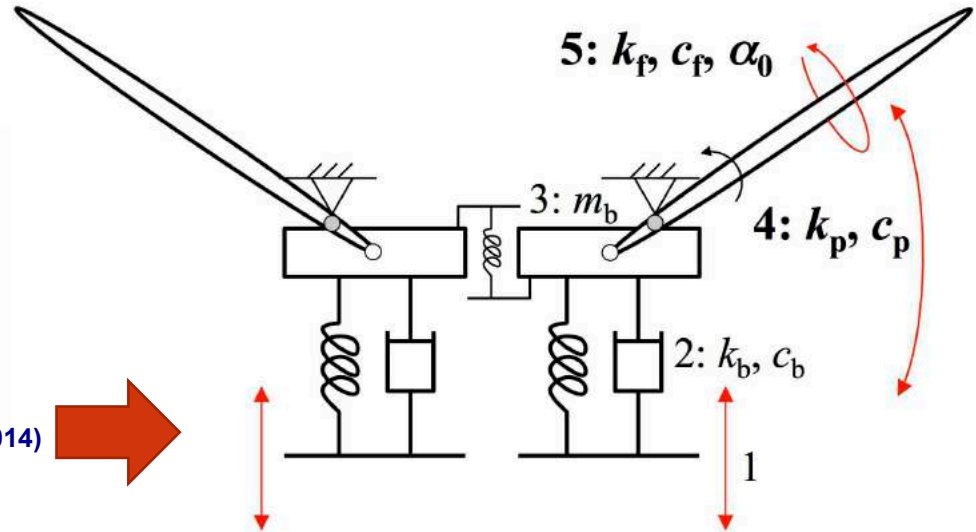
# Robustness in flexible wing hinge & musculoskeleton

## Dynamic Musculoskeletal Model (DMSM)

### flapping system

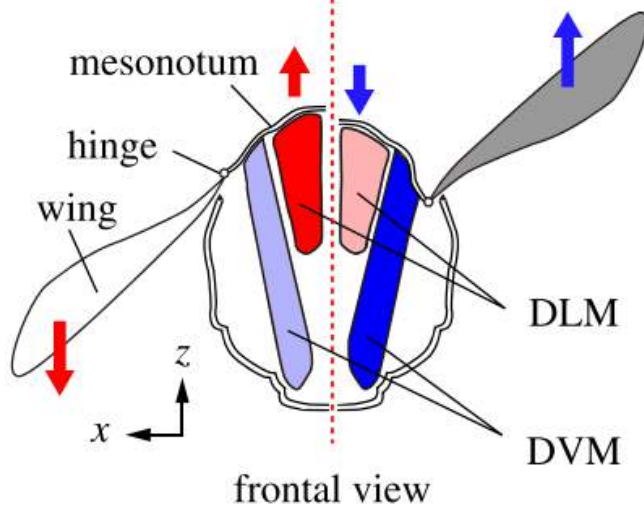


Walker et al. *PLoS Biology* (2014)



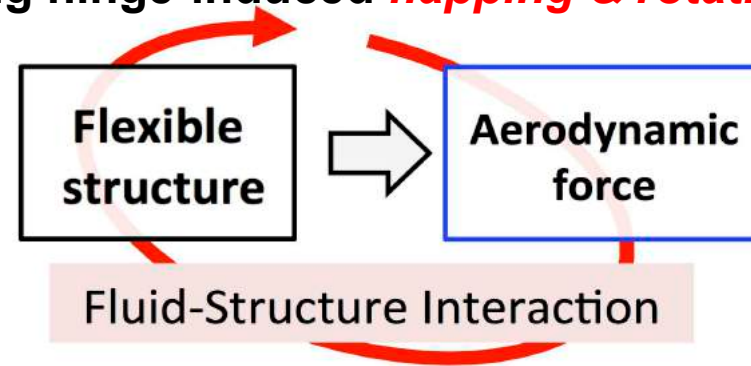
### Down-stroke

### Up-stroke



Ando et al. *Biology letters* (2016)

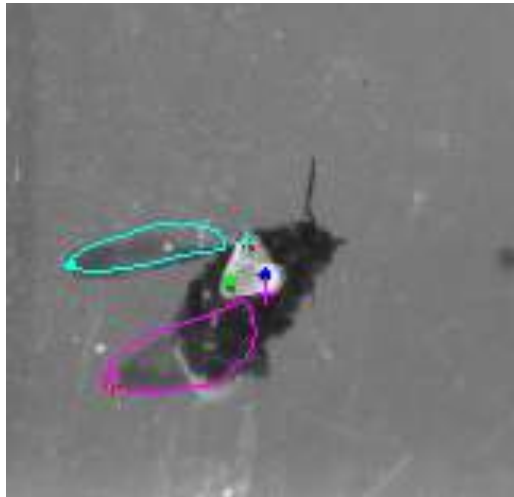
1. **Input oscillation**
- 2-3. Musculoskeleton: spring-mass-damper system
- 4-5. Wing hinge-induced **flapping & rotation**



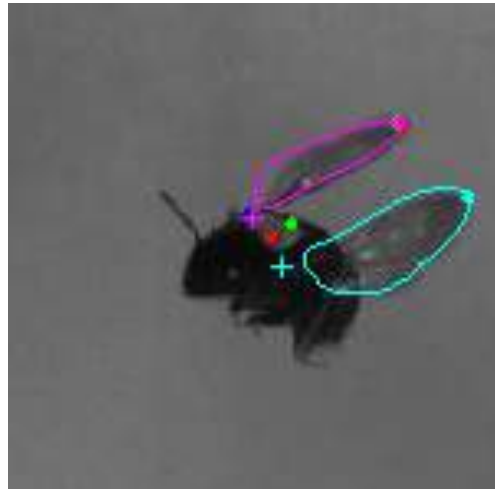
Enhancement of flight efficiency by elastic storage  
(Dickinson et al *Science* 1996)

# Reconstruction of wing kinematics

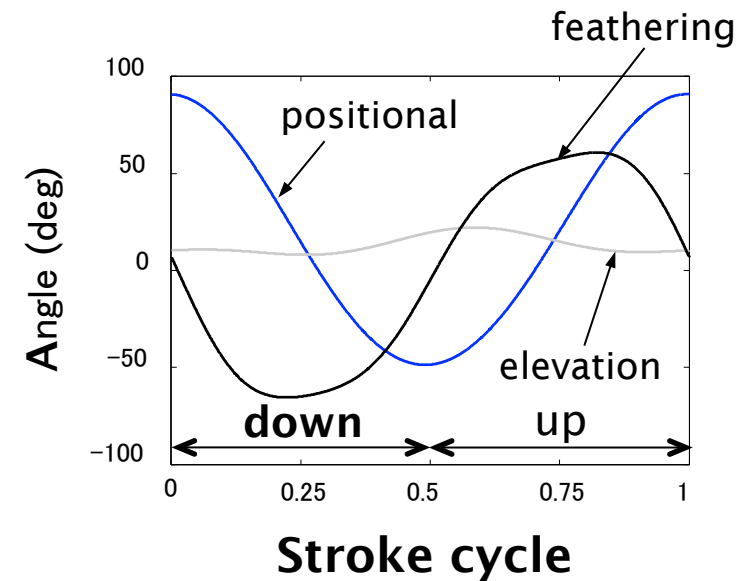
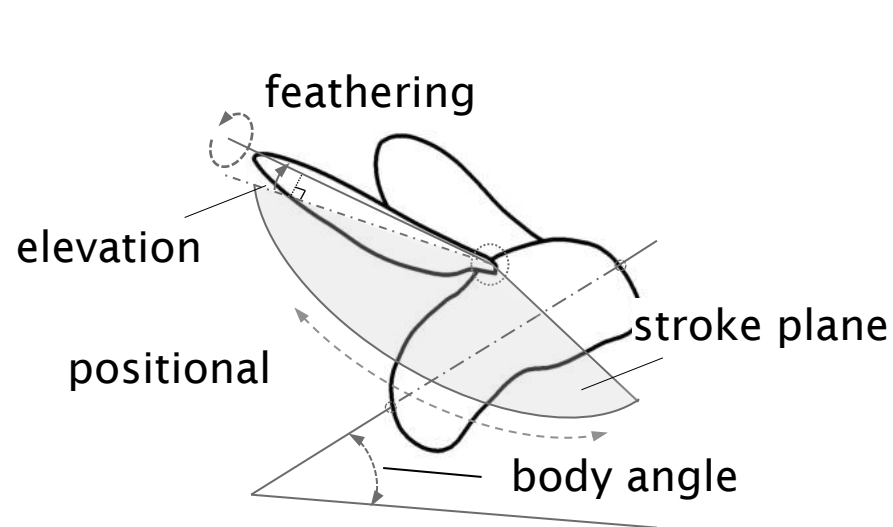
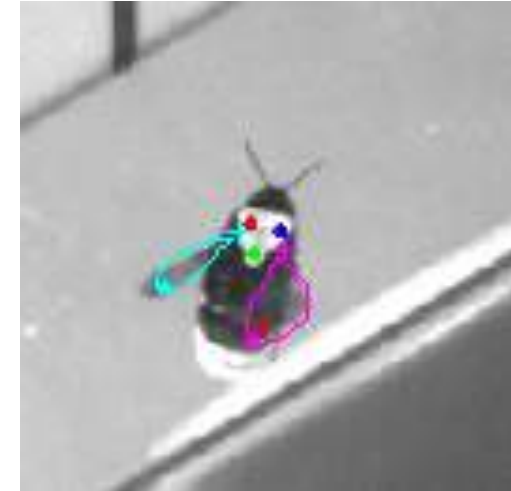
CAM1



CAM2

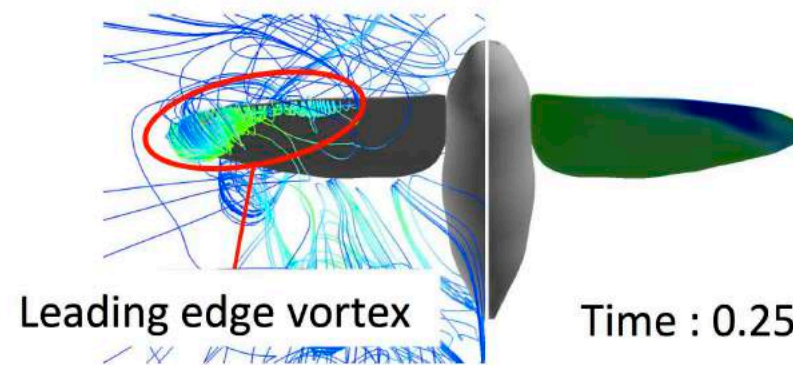
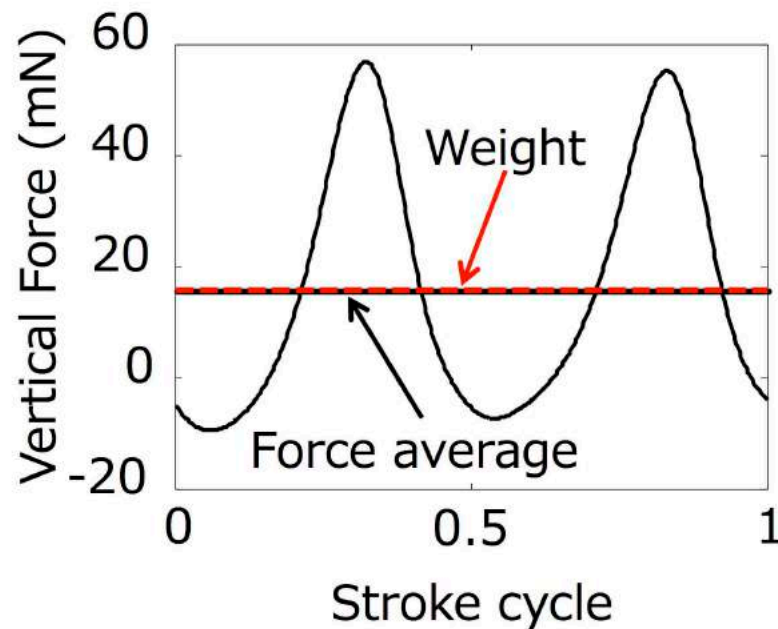
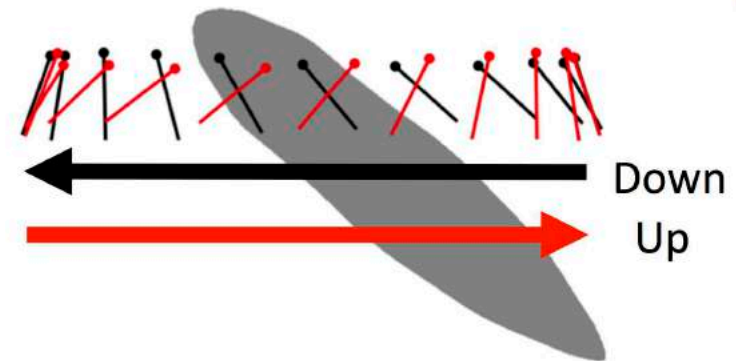
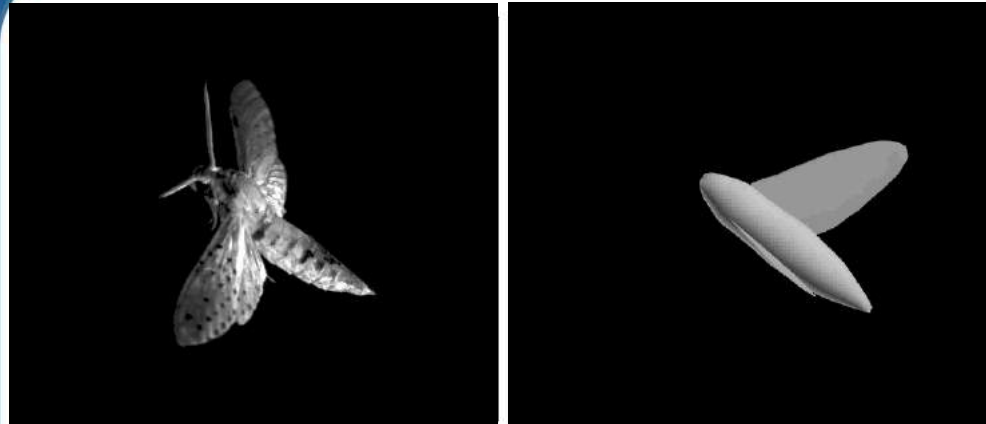


CAM3



# Robustness in flexible wing hinge & musculoskeleton

## Optimization result (amplitude ratio: 0.8)



Hovering state of hawkmoth  
can be achieved passively with DMSM.

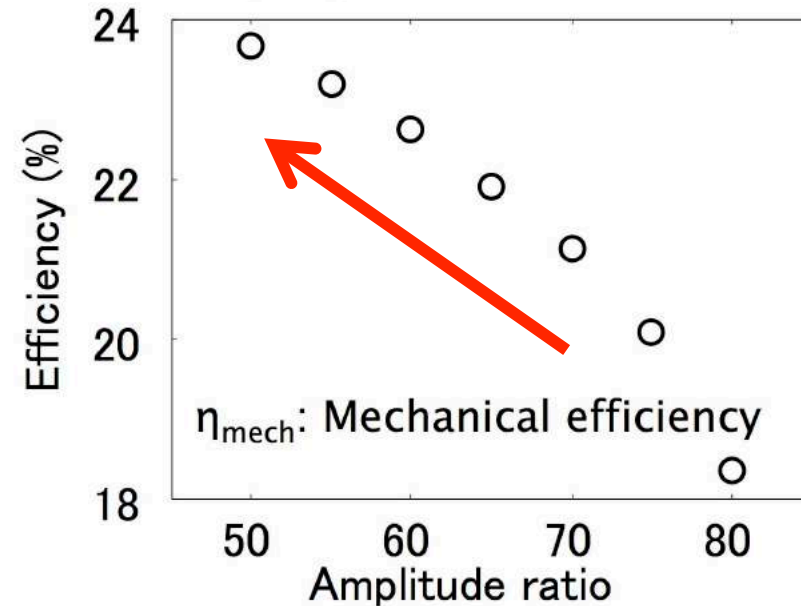
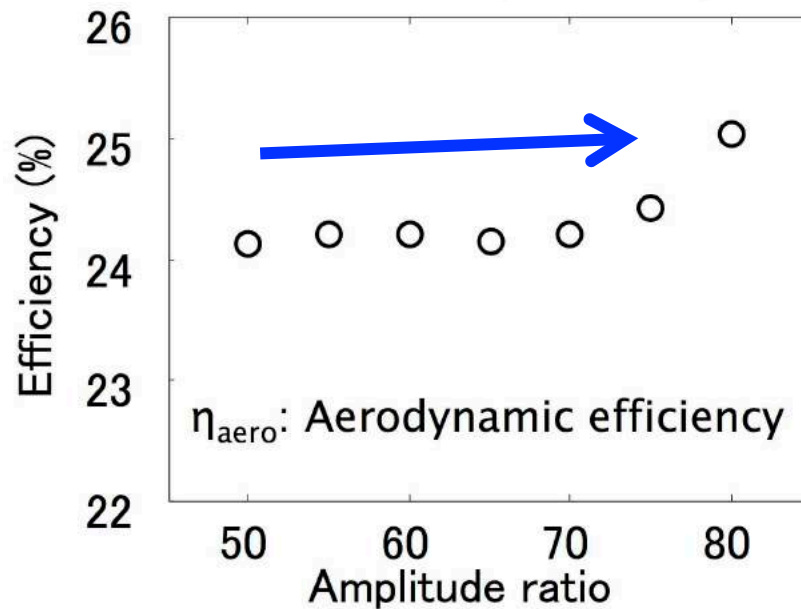
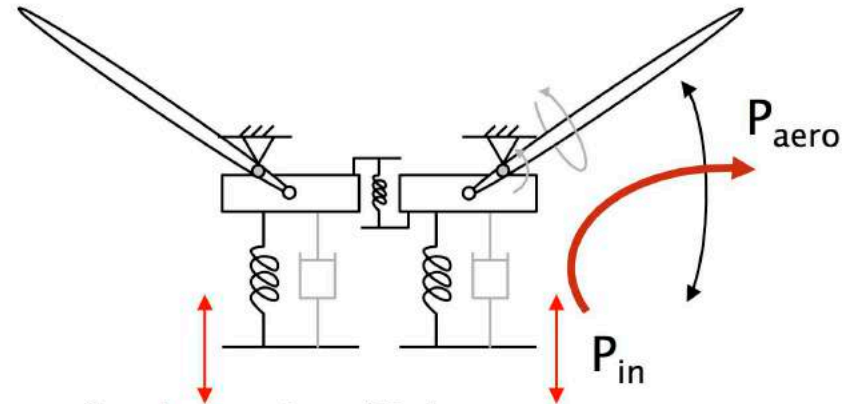
# Robustness in flexible wing hinge & musculoskeleton

## Relationship between inputs and efficiencies

▪  $\eta_{\text{aero}}: P_{\text{RF}}/P_{\text{aero}}$   
→ optimized wing kinematics

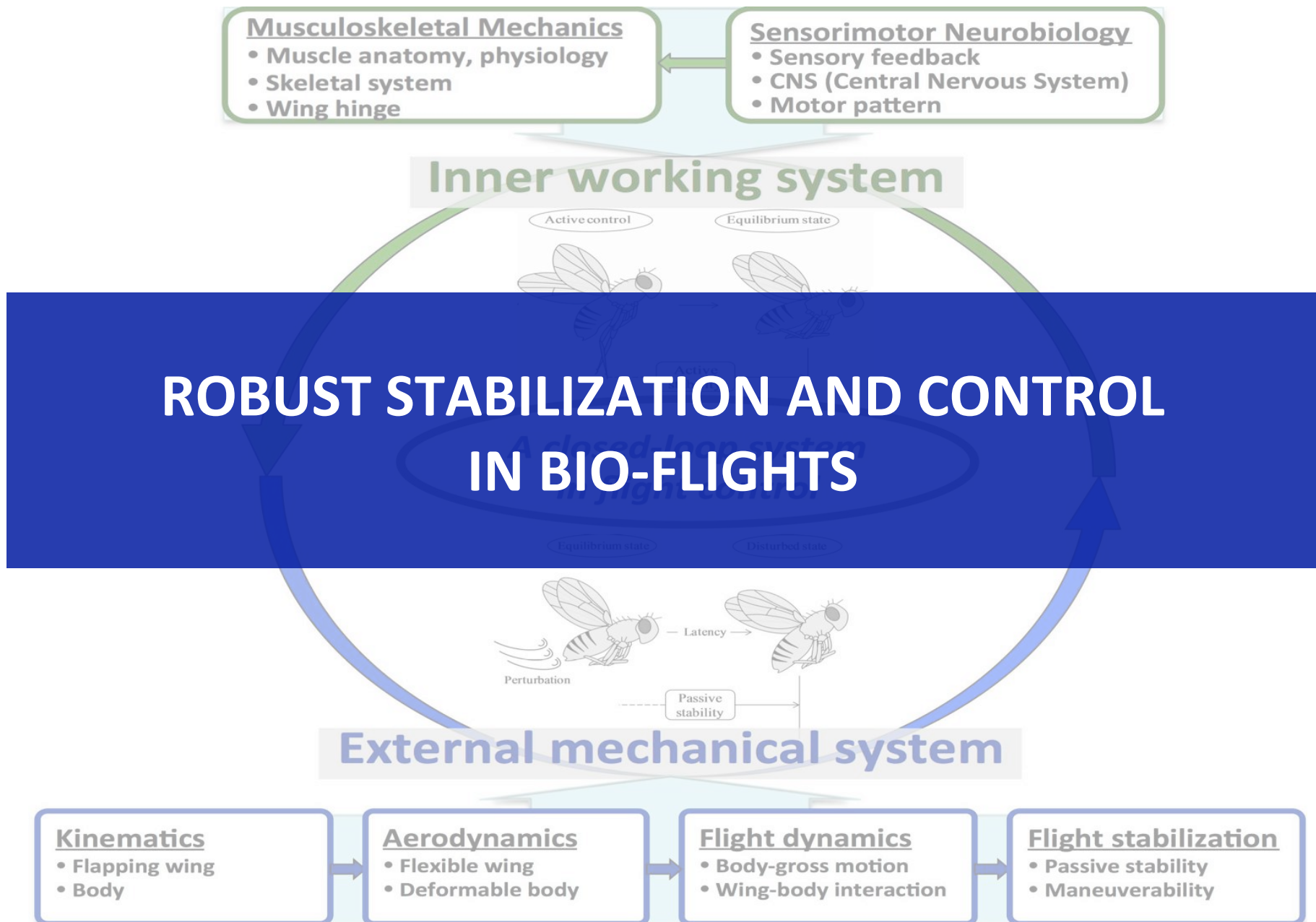
▪  $\eta_{\text{mech}}: P_{\text{RF}}/P_{\text{in}}$

→ minimized or optimized power for hovering flight



**Wing hinge flexibility can enhance mechanical efficiency.**

*In preparation 2018*

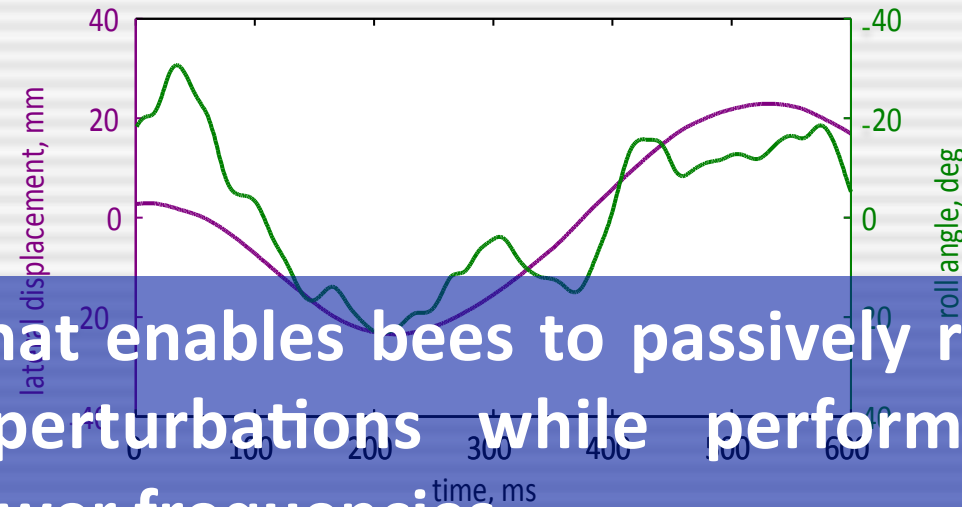


# Body dynamics of a bumblebee in forward flight

## Laminar inflow (steady)

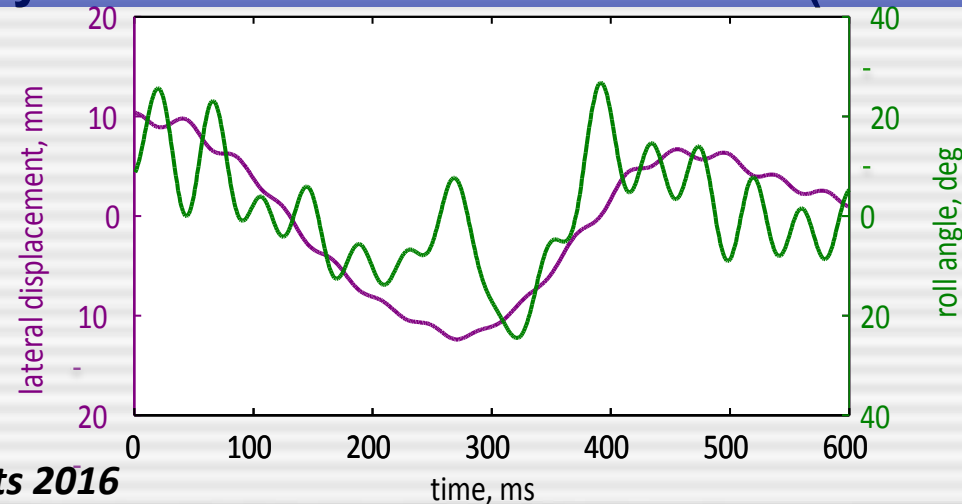
Wind tunnel experiment by S. Ravi et al.

A novel mechanism that enables bees to passively ride out high-frequency perturbations while performing active maneuvers at lower frequencies.



## Cylinder wake turbulence inflow (unsteady)

Lateral displacement  
Roll angle



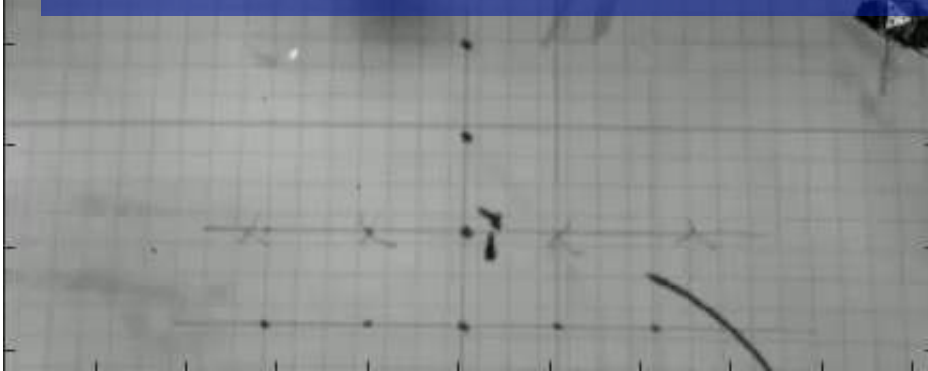
Ravi, Kolomenskiy, Liu et al Scientific Reports 2016



# Bumblebees minimize control challenges by combining active and passive modes in turbulence.

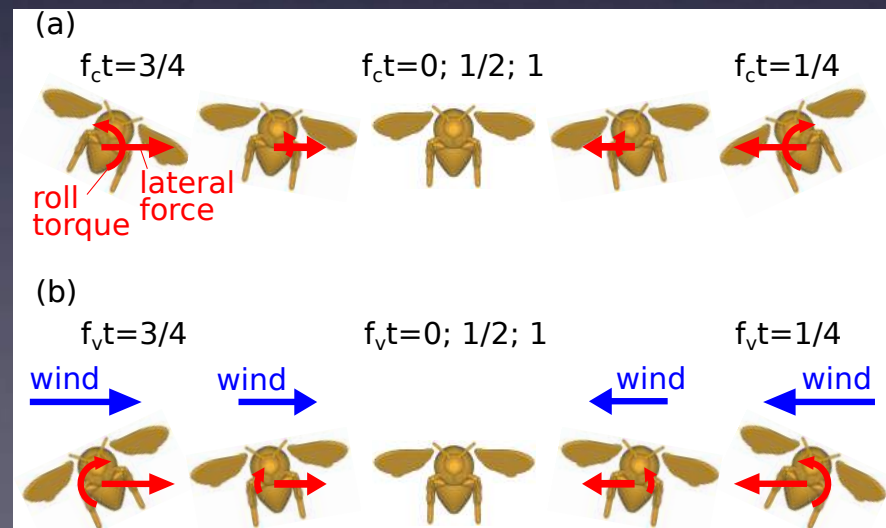
*(Ravi, Kolomenskiy, Liu et al Scientific Reports 2016)*

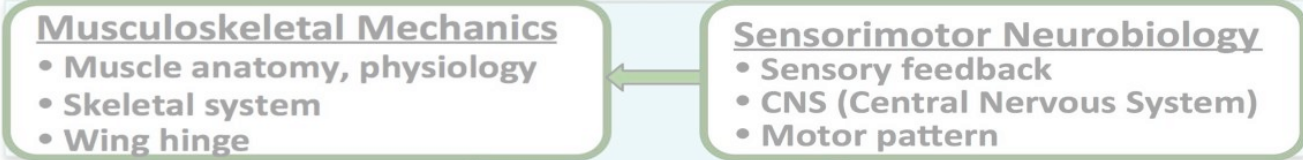
The capacity of maintaining stability by combining passive and active modes at different timescales provides a viable means for insects and machines to tackle the challenges posed by complex airflows.



*(a) low frequency casting maneuvers (helicopter model)*

*(b) high frequency buffeting in unsteady winds (sailboat model)*





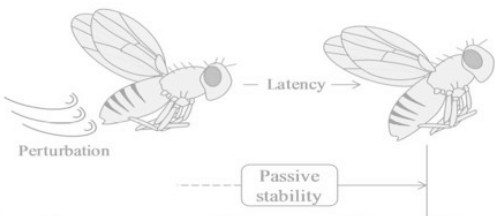
**Inner working system**

Active control      Equilibrium state



**ROBUST PASSIVE MECHANISMS  
IN INSECT-INSPIRED MAVS**

Equilibrium state      Disturbed state



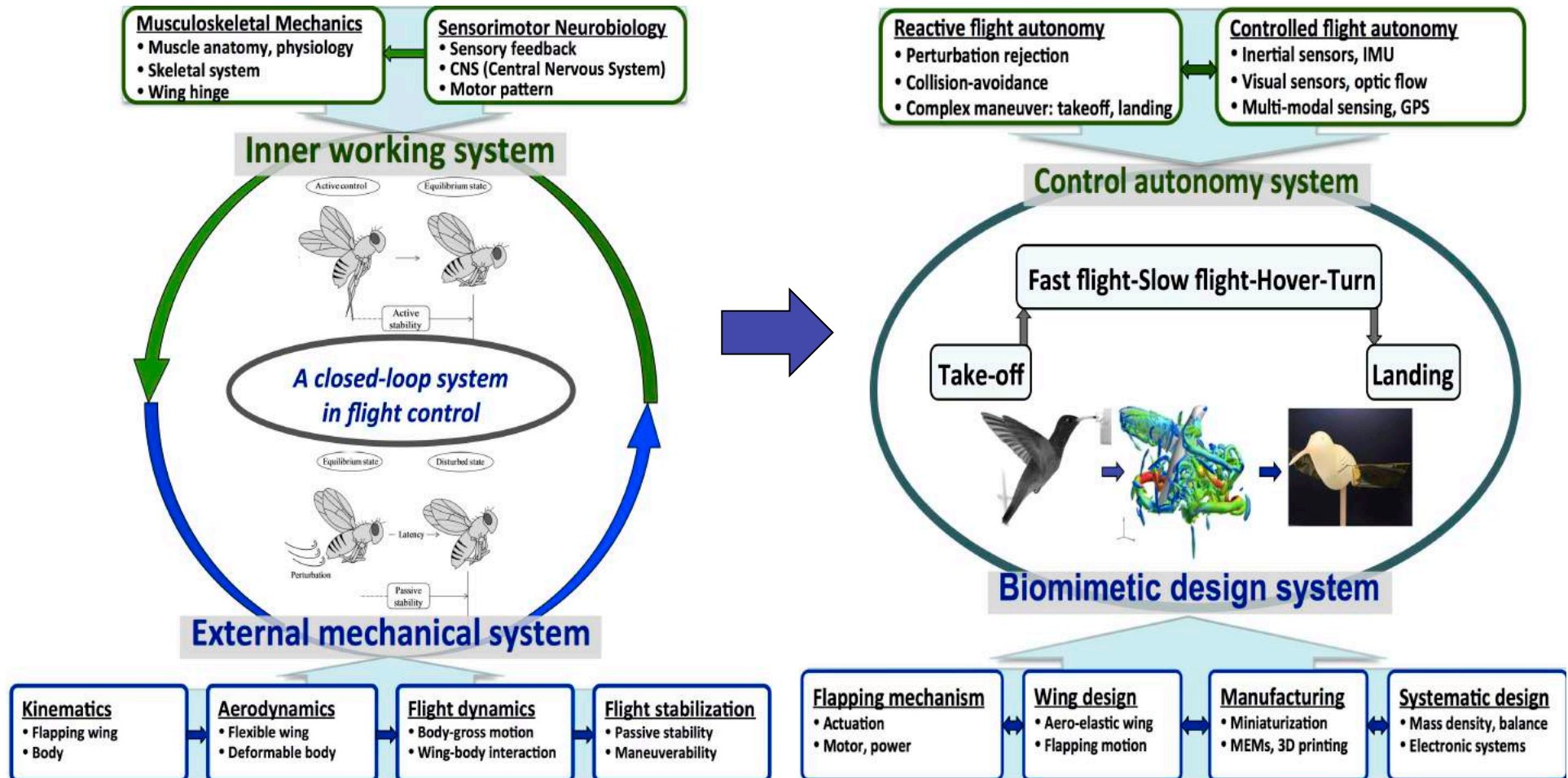
**External mechanical system**



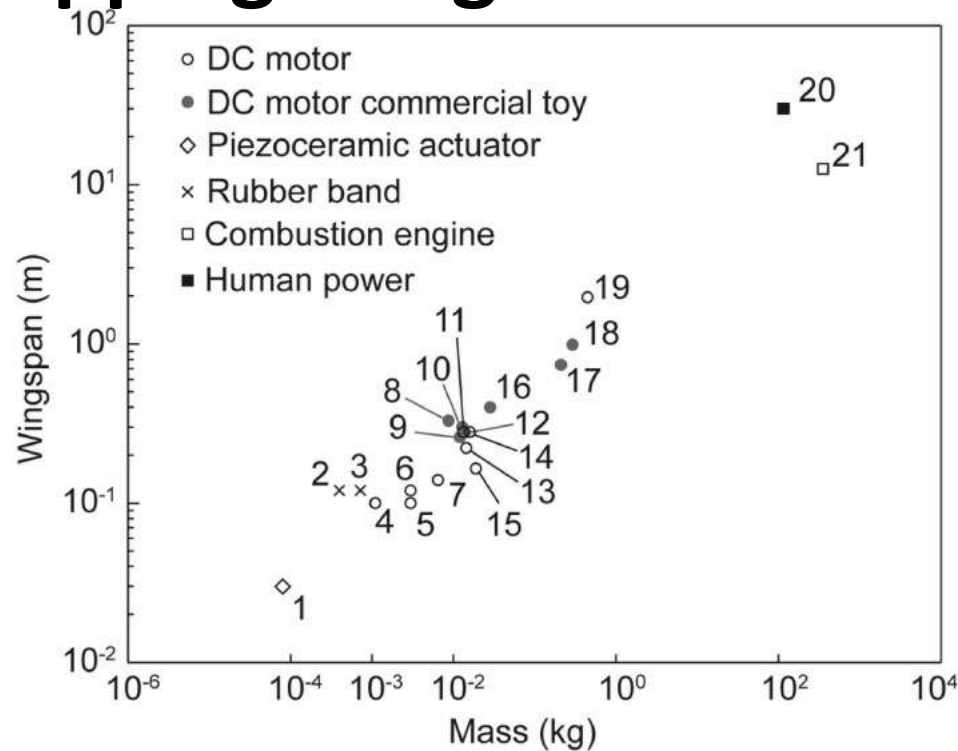
# Bio-inspired flight and Biomimetics

Bio-inspired flight system: integration of inner working system & external mechanical system

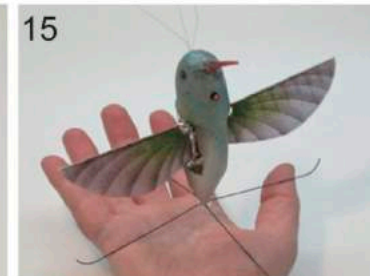
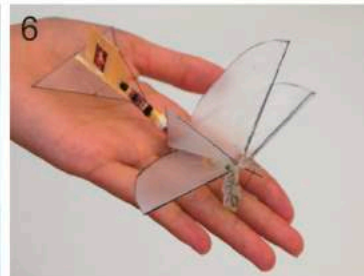
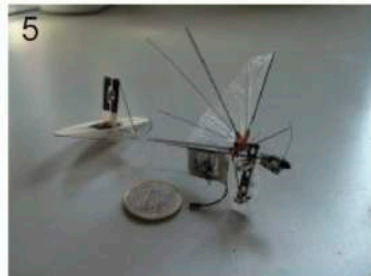
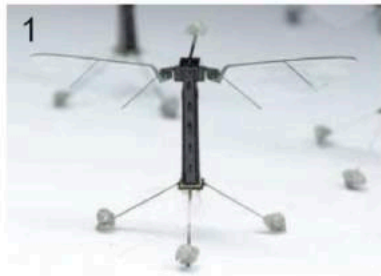
Strategy of bio-inspired system-based systematic design & manufacturing in MAVs

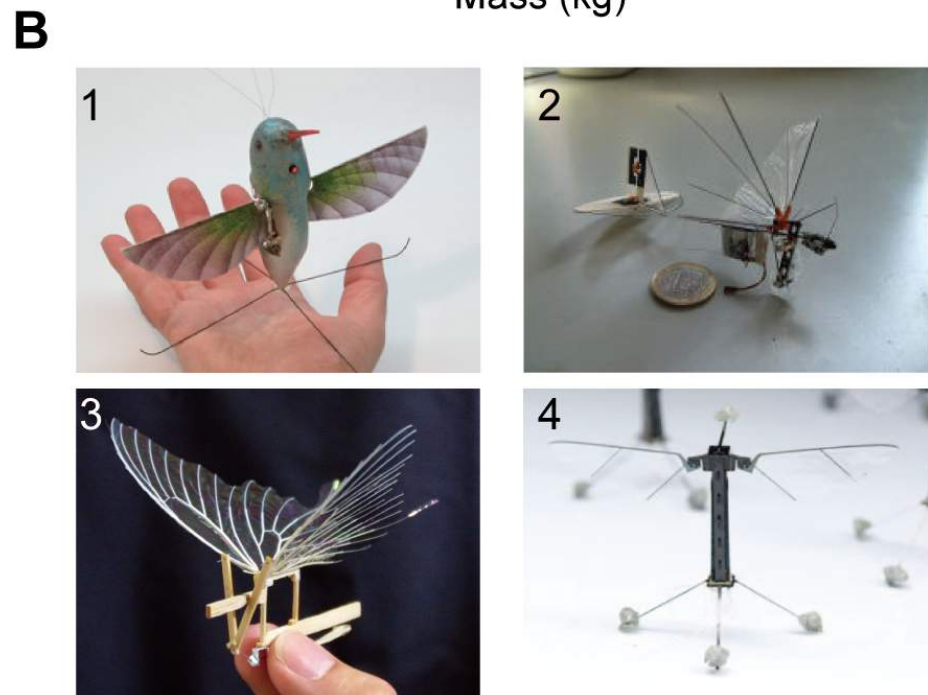
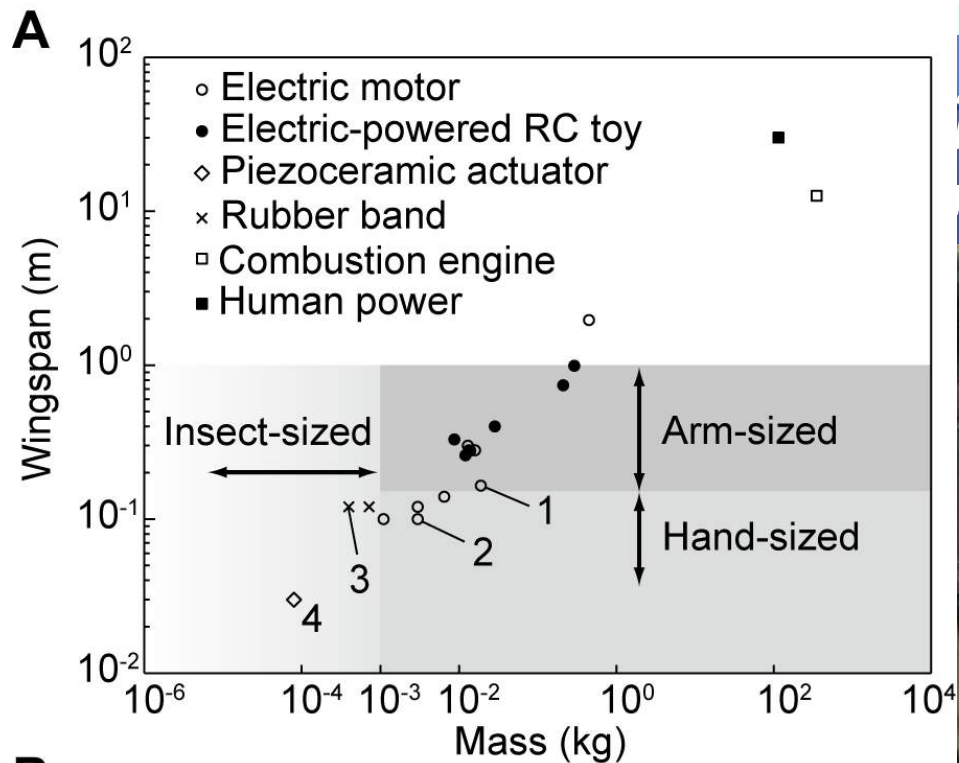


# Biomimetics in bio-inspired flight system: flapping-wing micro air vehicles and beyond



- |                         |                        |
|-------------------------|------------------------|
| 1. Microrobotic fly     | 11. I-Bird (modified)  |
| 2. Artificial butterfly | 12. E-bird             |
| 3. Artificial butterfly | 13. 14.6-g ornithopter |
| 4. 1-g ornithopter      | 14. DeIFly II          |
| 5. DeIFly Micro         | 15. Nano Hummingbird   |
| 6. 3-g ornithopter      | 16. Flytech Dragonfly  |
| 7. Microbat             | 17. Cybird P1          |
| 8. Avitron V2.0         | 18. Cybird P2          |
| 9. I-bird               | 19. SmartBird          |
| 10. i-Fly Vamp          | 20. Manned ornithopter |
|                         | 21. Manned ornithopter |





# flapping Micro Air Vehicle

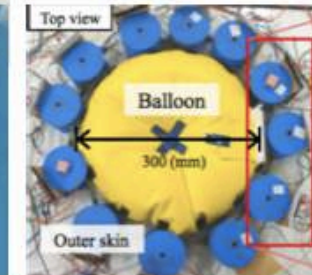
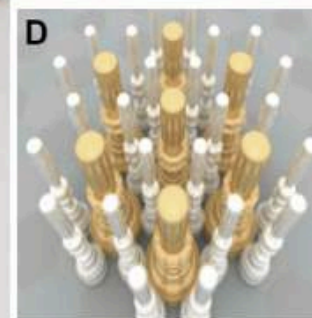
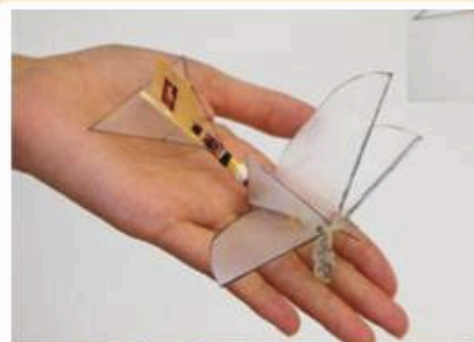
(Inspir. Biomim. 2012)

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Journal of the Japan Society of Mechanical Engineers

機械技術者の情報誌

<http://www.jsme.or.jp>



特集

生物に学ぶ機械工学

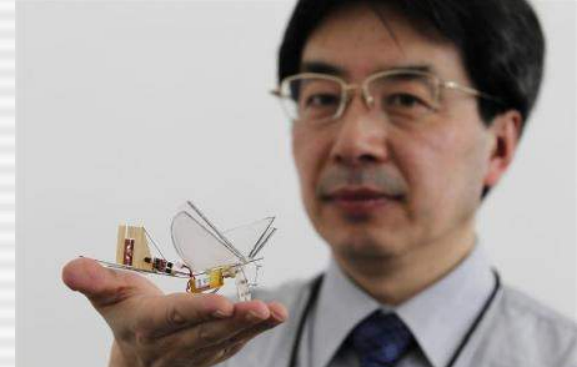
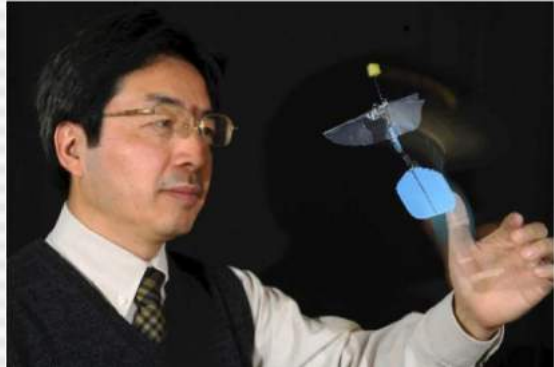
～持続可能な社会を拓くバイオミメティクスの世界～

2014

2 Vol.117  
No.1143

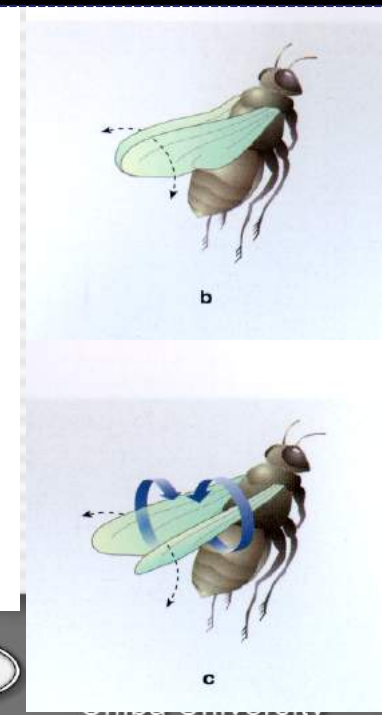
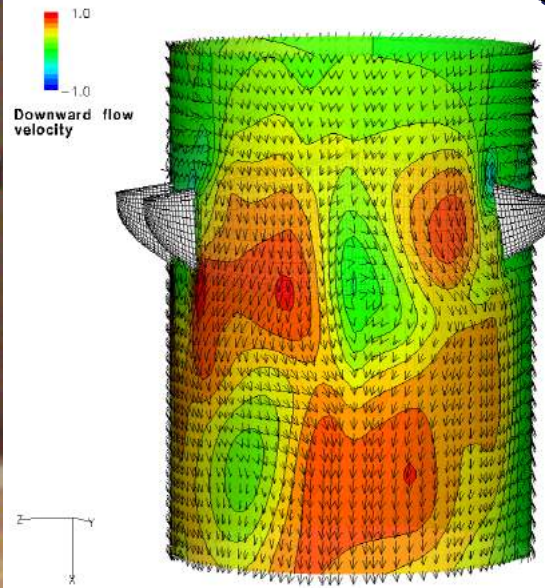
# Bio-inspired flapping-wing Micro Air Vehicles

A Hummingbird-inspired X-wing MAV (*Nakata&Liu et al BB 2012*)



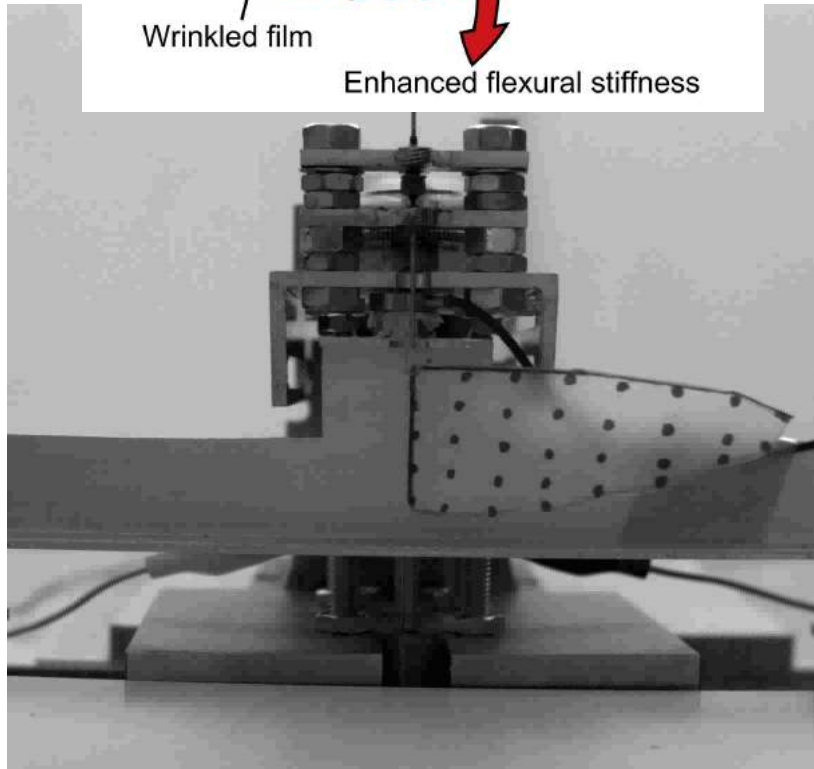
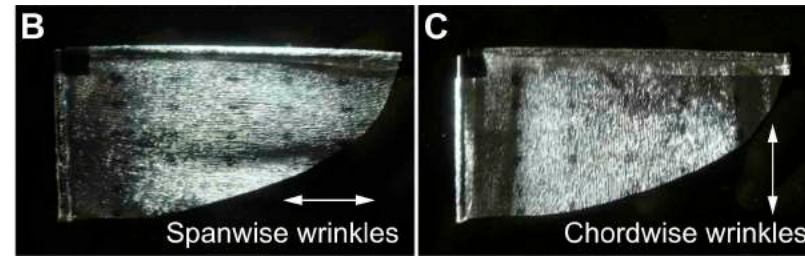
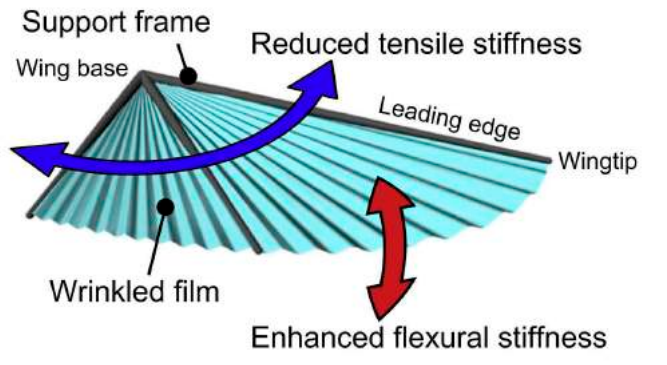
Mass Media: NHK, TBS-BS, 読売新聞, 朝日新聞, 日本経済新聞, 新华社, Reuters (2009 ~ 2014)

**Clap and fling**



# Developed 2<sup>nd</sup> generation two-winged fMAV: a [MEMS-based biomimetic wing design](#) (Tanaka&Liu et al BB 2015)

*Flexible flapping wings with self-organized microwrinkles*



**Artificial wing**

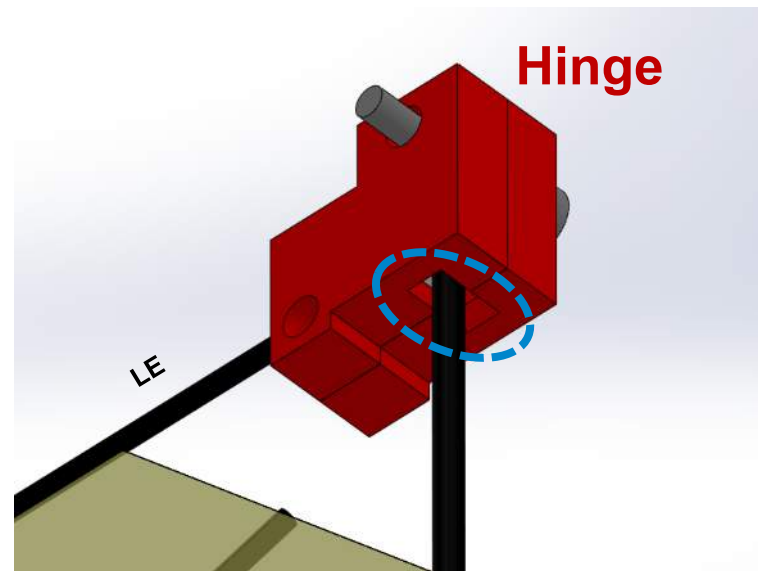
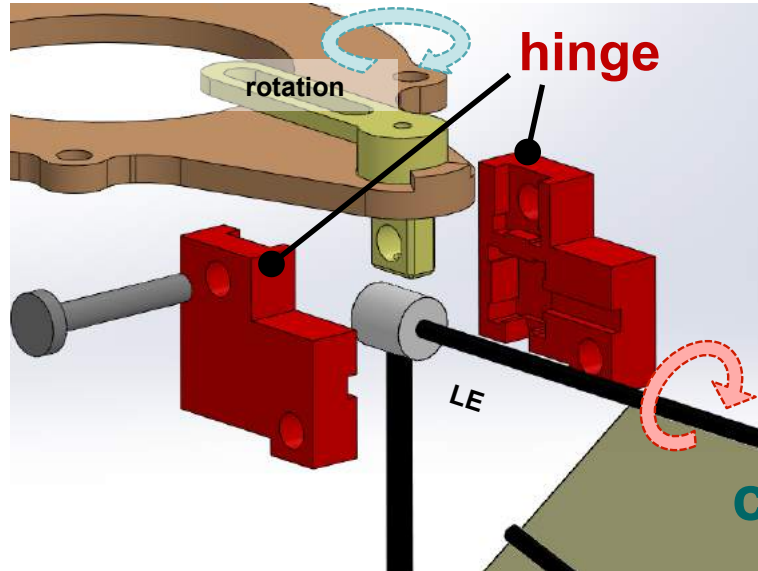
Bioinspired flight system Biomechanics



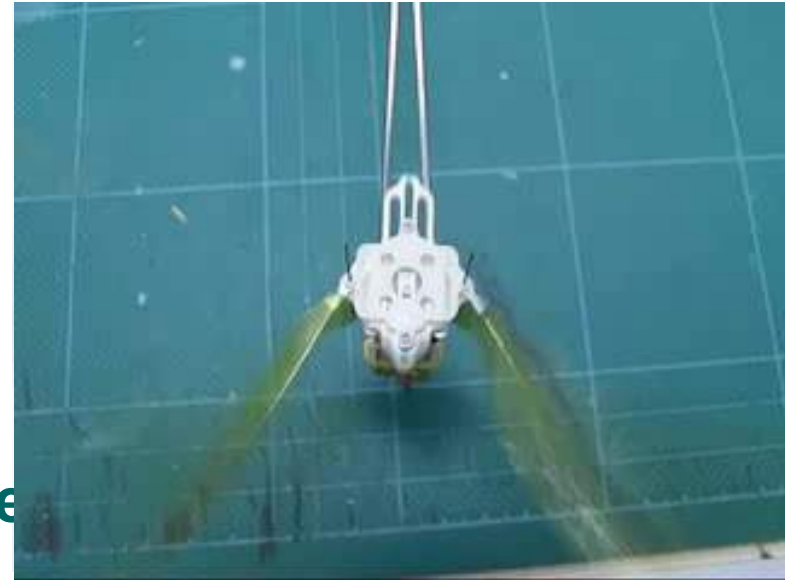
**Hummingbird**

# A novel flapping mechanism with planetary gear mechanisms and passive wing-hinges

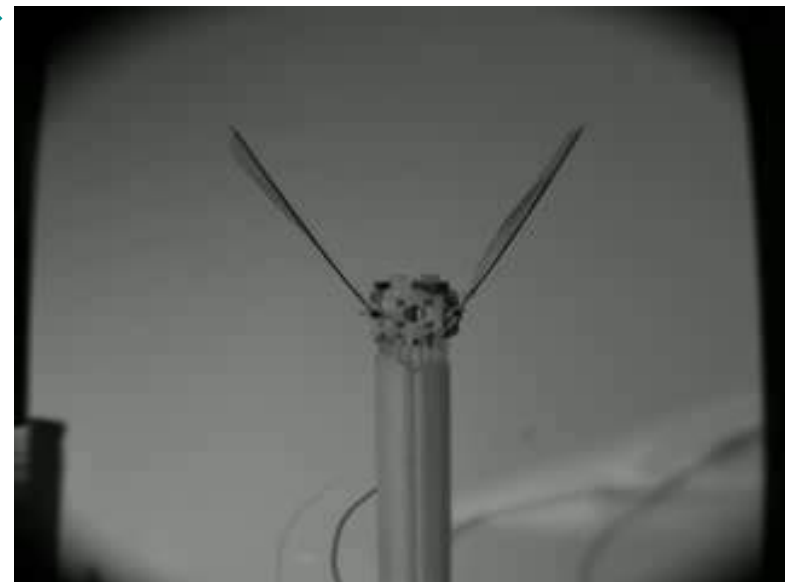
Passive wing-hinge



A planetary gear mechanism



combine



# Developing a novel flapping mechanism with paired hummingbird-inspired wings

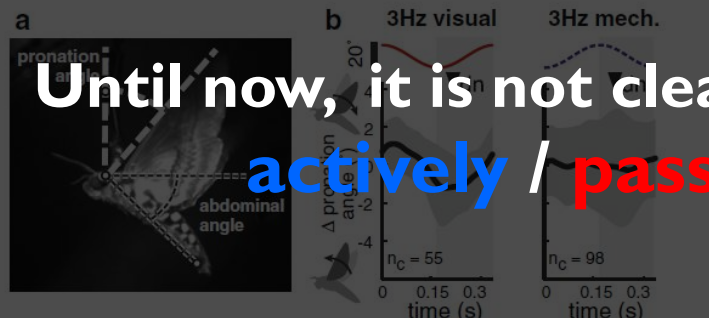


# Robustness passive mechanisms in insect-inspired MAVs

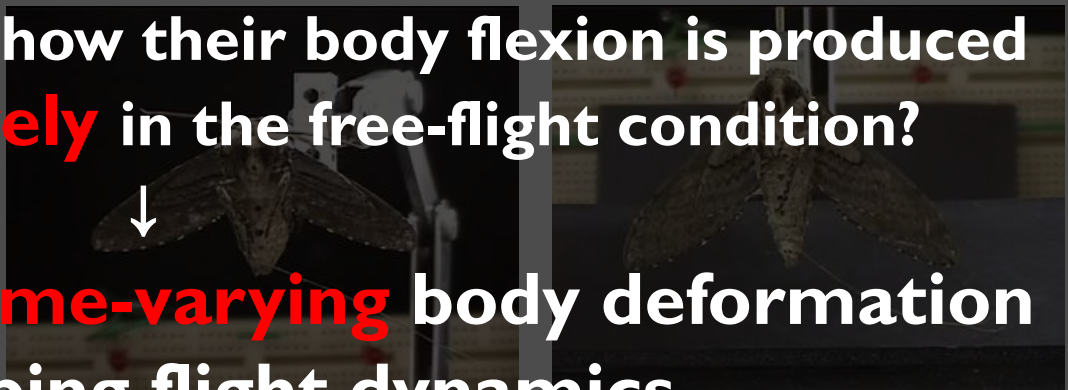
## *Body flexion of a hawkmoth*

It is known that real moths can actively alter body shape through the action of muscles at the thoracic-abdominal joint

The experimentally measured abdominal movements can help maintaining stable hovering flight in the mathematical model



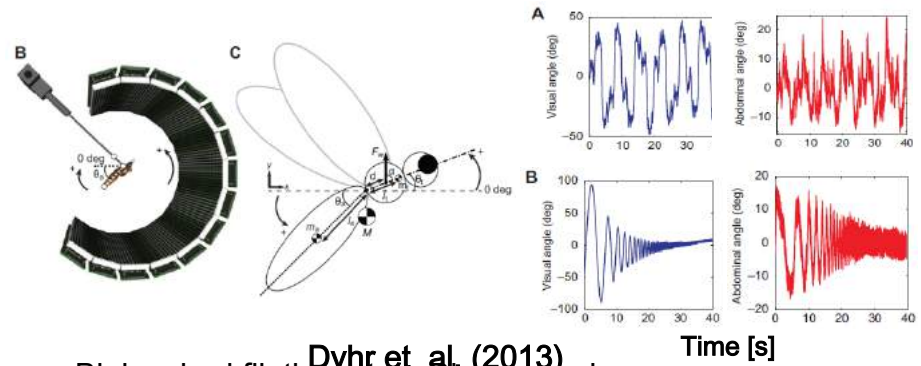
Until now, it is not clear how their body flexion is produced **actively** / **passively** in the free-flight condition?



Firstly, evaluate the **time-varying** body deformation on the flapping flight dynamics

Visual stimuli system

From Daniel Lab (2009)



Bioinspired flight system Biomechanics Dyhr et al. (2013) *J. Exp. Biol.*

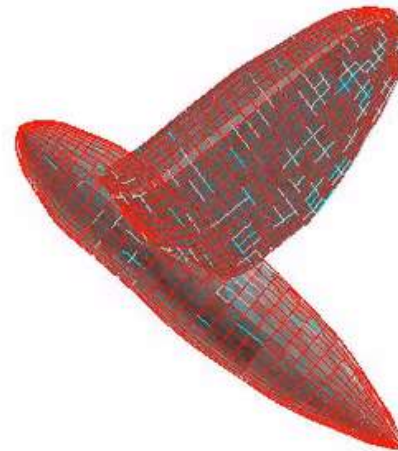
These experimental studies was conducted only **tethered flight** conditions and analysis in a **free-flight** condition with a flexible body has not been undertaken

# Flexible multi body dynamics: time-varying body models

Rigid

Flexible

Very Flexible

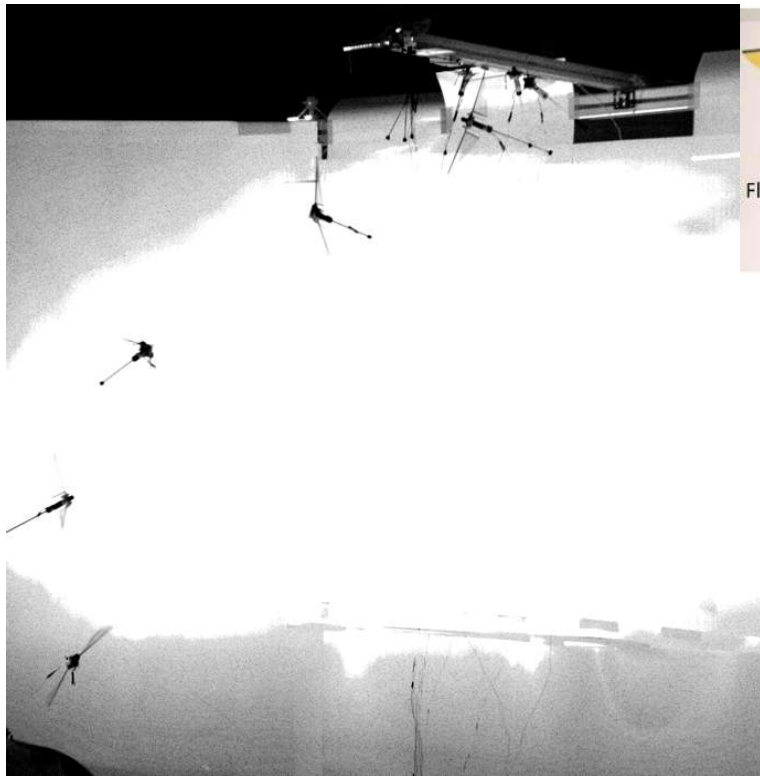


*Noda, Liu JBSE 2015*

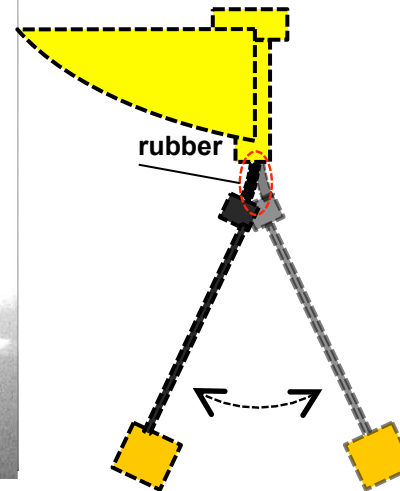
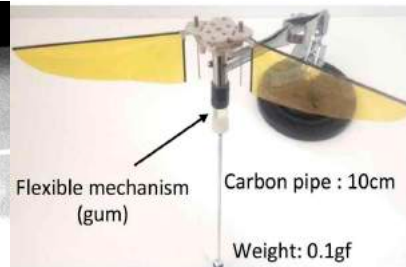
**$t/T = 0.02$**

# Robustness passive mechanisms in insect-inspired MAVs

## *Passive stabilization of bio-inspired micro-air vehicle using flexible body mechanism*



**Rigid body&tail**



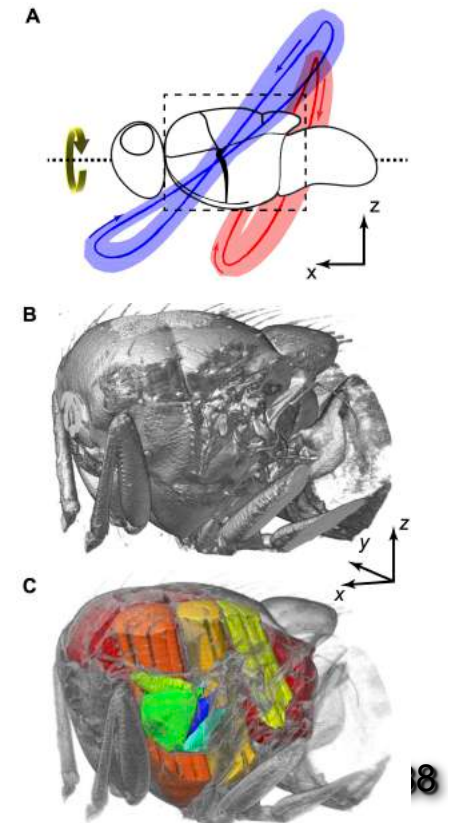
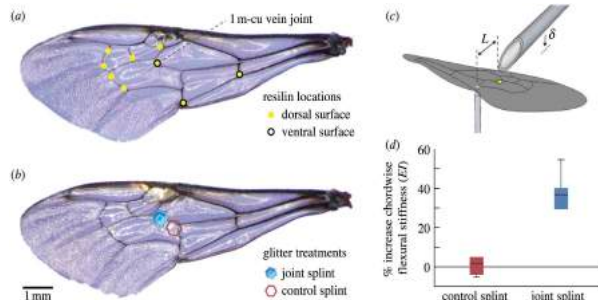
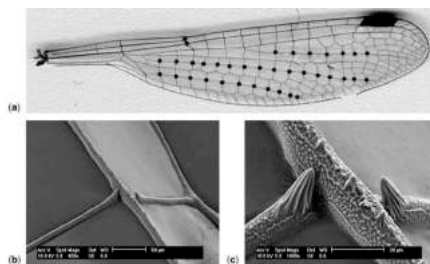
**Flexible body&tail (30Hz)**

*In preparation 2018*

# Robustness strategies in bio-inspired flight systems: morphology, dynamics and flight control

## Challenges and Future Opportunity (1/2)

Flexible structures (body, wing, vein, hinge, motor, muscle, sensor, neuron) are an essential and sophisticated design in bio-inspired flight systems, which offer promises to design smart and multi-functional autonomous systems and robots for engineering applications.

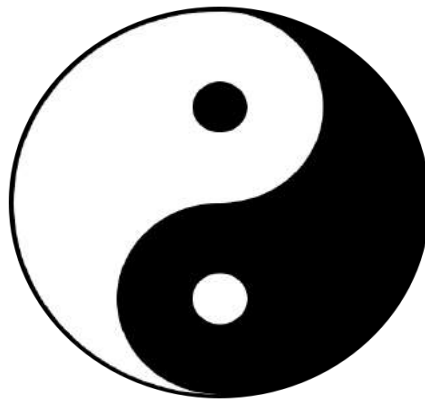


# Robustness strategies in bio-inspired flight systems: morphology, dynamics and flight control

## Challenge and Future Opportunities (2/2)

**Passive and Active Mechanisms** (aerodynamics, stability, control, sensing, modulating) work interactively and complementarily in biological systems, which are robust, efficient and sustainable.

阳(陽)Yang  
(positive-active)



阴(陰)Yin  
(negative-passive)

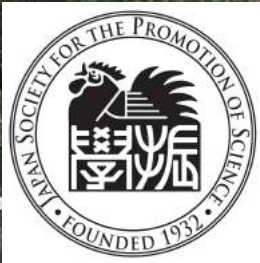
**The Chinese philosophy** might have already given a sophisticated solution to this: 太極圖 the principles of Ying (**negative-passive**) and Yang (**positive-active**).

# Acknowledgements

Biomechanical Eng. Lab, Chiba University

Sponsors and Collaborators:

科研費  
KAKENHI



国立大学法人 千葉大学  
National University Corporation  
Chiba University