Aerodynamics and control in insect flight

Richard J Bomphrey
The Structure and Motion Laboratory

>800 m² (and 600 m² more this year)
Early days
Insect flight as a model system

- Wing morphology and kinematics
- Aerodynamic forces
- Activate muscles
- 3D locomotion
- Neural control
- Rich sensory input

movie: J. Zeil
Tracing the wake of a flying bird

1979

N. V. Kokshaysky

The general configuration of a wake is given, but no measurements have been made: in general, to extract some quantitative information from the wake structure, a more precisely documented picture of the dynamics of its formation is needed.
MOMENTUM AND ENERGY IN THE WAKE OF A PIGEON (COLUMBA LIVIA) IN SLOW FLIGHT

BY G. R. SPEDDING*, J. M. V. RAYNER AND C. J. PENNYCUICK†

900 stereo pairs
2500 bubble images in each stereo pair
5 stereo pairs fully analysed
Tobacco hawkmoth vortex wake over a wingbeat cycle.

2005
The flow around the wings and thorax of *Manduca sexta* in late downstroke.
The four classes of leading-edge vortex described to date.
Leading-edge vortices in biology

Hawkmoth: 65%
Fruit fly: 45%
Bat: 40%
Hummingbird: 15%

Bomphrey et al 2005
Warrick et al 2005
Muijres et al 2008
Lentink et al 2009
Kinematics of the desert locust

Walker et al JRS: Interface (2009)
Young et al Science (2009)
Kinematics of the desert locust

Walker et al. *JRS: Interface* (2009)
CFD validated with close match

- Qualitative and quantitative agreement with full-fidelity model

- Kinematic parameters changed to test corrugation, twist, and bending in the wing...

Young et al Science (2009)
Fully deforming wings have better power economy.

If locusts evolved from an ancestor with rigid wings, their subsequent compliance has *inhibited* leading-edge separation and improved lift power economy by approx. 70%

This stems from a number of sources, including:

- CAMBER MODULATION
- REDUCED SEPARATION at the leading edge
- modulation of spanwise ANGLE OF ATTACK

Young et al *Science* (2009)
Span efficiency

Lift

Spanwise CL

Planform

Downwash angle

Hoerner & Borst (1987)
Span efficiency

$e_i = 0.89$
Span efficiency: tr-PIV

Ever increasing detail of model species tells us relatively little compared with identifying trends and overarching themes.
Six species of hawkmoth

H. furciformis

M. stellatarum

H. euphorbiae

D. elpenor

S. ligustri

M. sexta
Six species of hawkmoth

- *H. fuciformis*
- *M. stellatarum*
- *H. euphorbiae*
- *D. elpenor*
- *S. ligustri*
- *M. sexta*
Six species of hawkmoth

- *H. fuciformis*
- *M. stellatarum*
- *H. euphorbiae*
- *D. elpenor*
- *S. ligustri*
- *M. sexta*
Six species of Odonata

Bomphrey R J et al Phil Trans Roy Soc B (invited for 2016)
Swift aerodynamics

P. Henningsson (photo: A. Hedenström)
Swift aerodynamics

Henningsson, Hedenström and Bomphrey 2013
sensory systems
Aircraft vs Insect sensory systems

F-35 Joint Strike Fighter
In contrast, insect sensory systems are highly non-orthogonal.
Optic Flow
Optic Flow

Mode Sensing Hypothesis: Krapp, Taylor & Humbert, 2012

Krapp, 1996
Trade-off

**STABILITY**

Modes of motion

1. Glide: stable

2. The Phugoid
   - unstable oscillatory mode
   - exchange of kinetic and potential energy

3. Banked Turn; Spiral mode
   - unstable divergent mode

..there are others
Flight control: example questions

What visual information is important to insects for controlling their flight?

How is the flight control related to flight dynamics?
Does the control system match the modes of motion?

Longitudinal modes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Gain to stabilise</th>
</tr>
</thead>
<tbody>
<tr>
<td>forward velocity</td>
<td>0.19</td>
</tr>
<tr>
<td>vertical velocity</td>
<td>-</td>
</tr>
<tr>
<td>pitch rate</td>
<td>0.26</td>
</tr>
<tr>
<td>pitch angle</td>
<td>0.17</td>
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</tbody>
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## Insect modes of motion

### Longitudinal modes

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### Lateral modes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Gain to stabilise</th>
</tr>
</thead>
<tbody>
<tr>
<td>side velocity</td>
<td>∞</td>
</tr>
<tr>
<td>roll rate</td>
<td>∞</td>
</tr>
<tr>
<td>yaw rate</td>
<td>-</td>
</tr>
<tr>
<td>roll angle</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Model data from: Zhang & Sun (2010)
Black box approach

Flight control system

Sensory input

Force output

Windsor, Bomphrey and Taylor (2013)
Animation and Movie courtesy of Shane Windsor
Windsor, Bomphrey and Taylor (2013)
Frequency response

Magnitude = \frac{\text{Response}}{\text{Stimulus}}

Position or rate response?

Windsor, Bomphrey and Taylor (2013)
Axis comparison

<table>
<thead>
<tr>
<th>Axis</th>
<th>What is required to stabilise flight?</th>
<th>Measured response</th>
</tr>
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<tbody>
<tr>
<td>Roll</td>
<td>Roll angle</td>
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</tr>
<tr>
<td>Pitch</td>
<td>Pitch angle</td>
<td>Pitch angle</td>
</tr>
<tr>
<td></td>
<td>Pitch rate</td>
<td>Pitch rate</td>
</tr>
<tr>
<td></td>
<td>Forward velocity</td>
<td></td>
</tr>
<tr>
<td>Yaw</td>
<td>Passively stable</td>
<td>Yaw angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yaw rate</td>
</tr>
</tbody>
</table>

Windsor, Bomphrey and Taylor (2013)
Dr Toshiyuki Nakata (Postdoc)
Dr Nathan Phillips (Postdoc)
Dr Jorn Cheney (Postdoc)
Ms Florence Albert-Davie (PhD student)
Ms Hannah Safi (PhD student)
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