Flapping around in a wind tunnel

Recent research on biological flight at the University of Liège

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Introduction

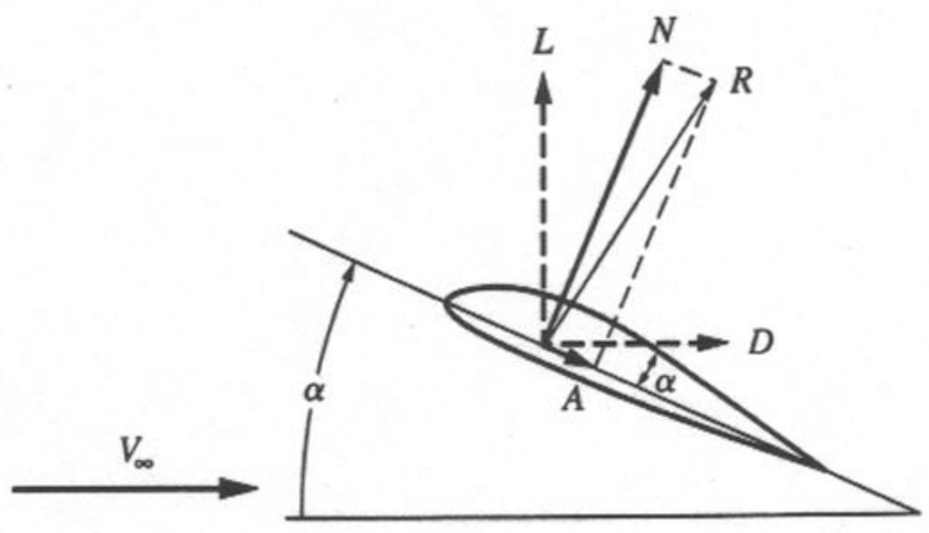
- Aeronautical engineers and biologists have collaborated several times in the past on investigations of animal flight.
- Several wind tunnel tests have been carried out on wings, bodies etc.
- The main limitation of these experiments is the fact that they were mostly static:
  - The wings did not move in the wind tunnel.
  - Birds, bats, insects do flap their wings.
- Even theoretical modelling has usually only considered static wings:
  - Good enough for gliding flight
  - Not good for any other type of flight:
    - Take-off, landing
    - Cruise (e.g. migratory flight)
    - Hovering
    - Manoeuvres.

Some basic facts

- Static wings generate lift and drag.
- These forces depend on:
  - Airspeed.
  - Flight altitude (air density).
  - Wing geometry:
    - Profile (cross-sectional shape)
    - Planform (view from the top)
  - Angle of attack (angle between wing and airflow).
- Flapping wings generate lift but they can also generate thrust.
- These forces depend on all the previous characteristics plus:
  - Flapping amplitude.
  - Flapping (and pitching) frequency.
  - Pitching amplitude.
  - Pitching phase with respect to flapping.
- All of this is complicated even further by the fact that wings are flexible and therefore deform both under static and dynamic conditions.

Lift and drag

- Lift, L, is perpendicular to wind.
- Drag, D, is parallel to wing.
- Angle of attack is α.
- For small angles of attack L is proportional to α.
- We usually quote the lift and drag coefficients.
  - Air density, ρ, airspeed V_∞, chord c.



$$c_l = \frac{L}{\frac{1}{2}\rho V_\infty^2 c}$$

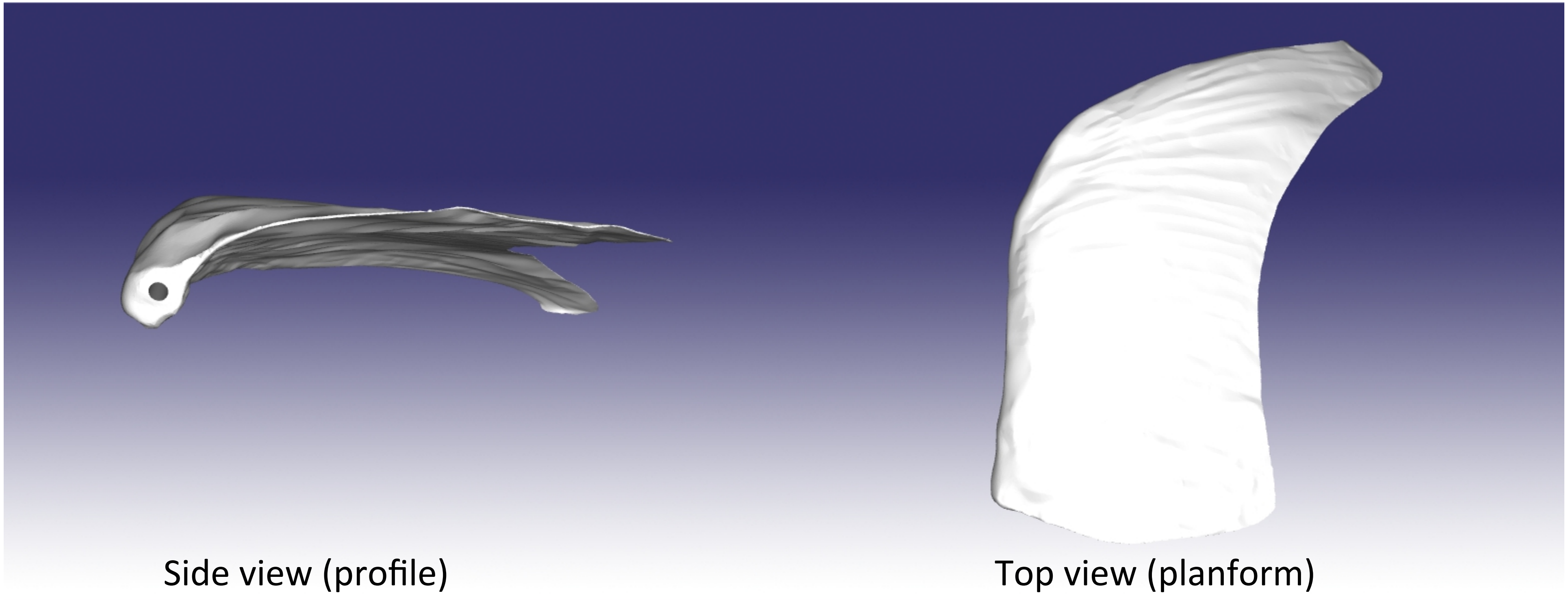
$$c_d = \frac{D}{\frac{1}{2}\rho V_\infty^2 c}$$

Example: Goose wing

- Visual comparison between a normal wing and the laminated wing.
- The two are qualitatively similar, even if the vacuum bag process may have altered the values of some of the properties.

- A wing from a barnacle goose was put in a vacuum bag and laminated.
- The laminated wing was then scanned using an optical 3D scanner.

Goose wing scan

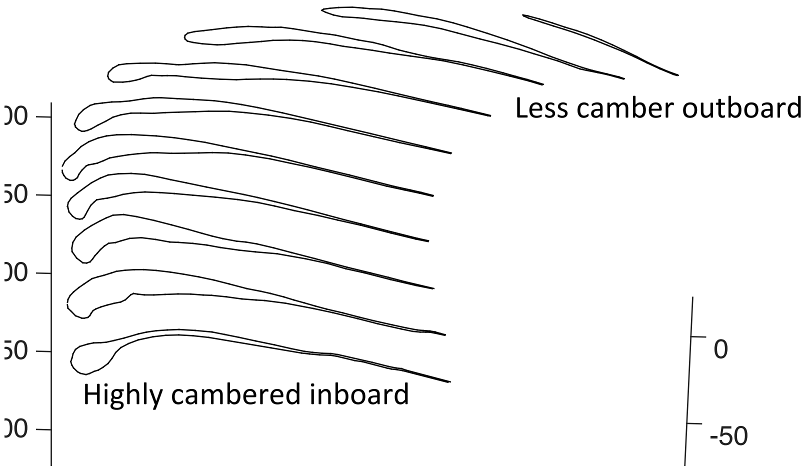

Side view (profile)

Top view (planform)

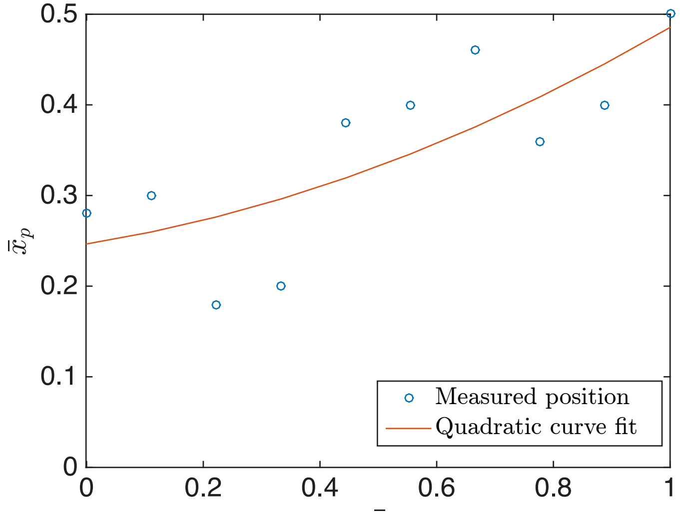
- The profile changes along the span:
  - Highly cambered near the root.
  - Low camber near the tip.
- Wing planform:
  - Straight inboard but sweeps back outboard.
  - Tapered.
  - Twisted.

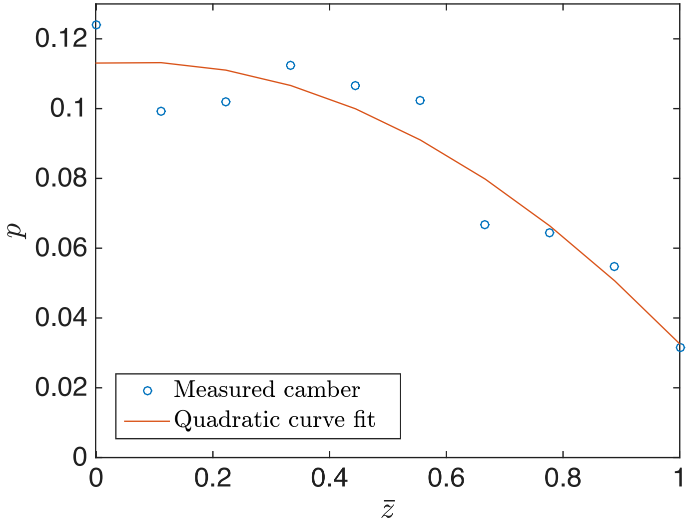
Wing analysis

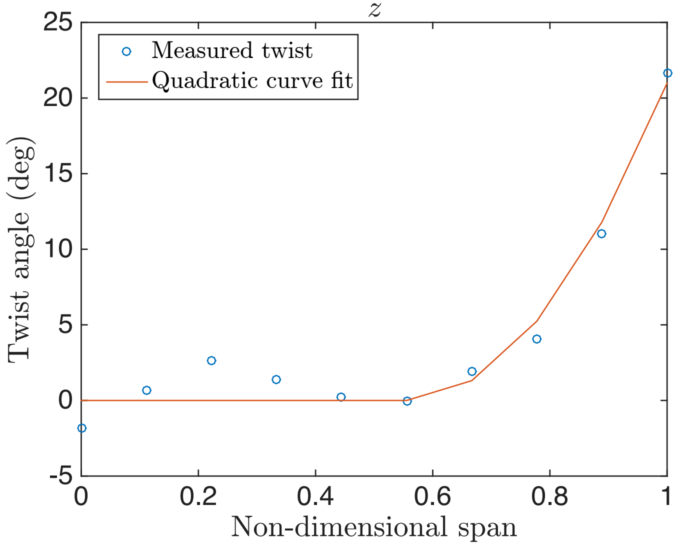
Wing profile shapes


Less camber outboard

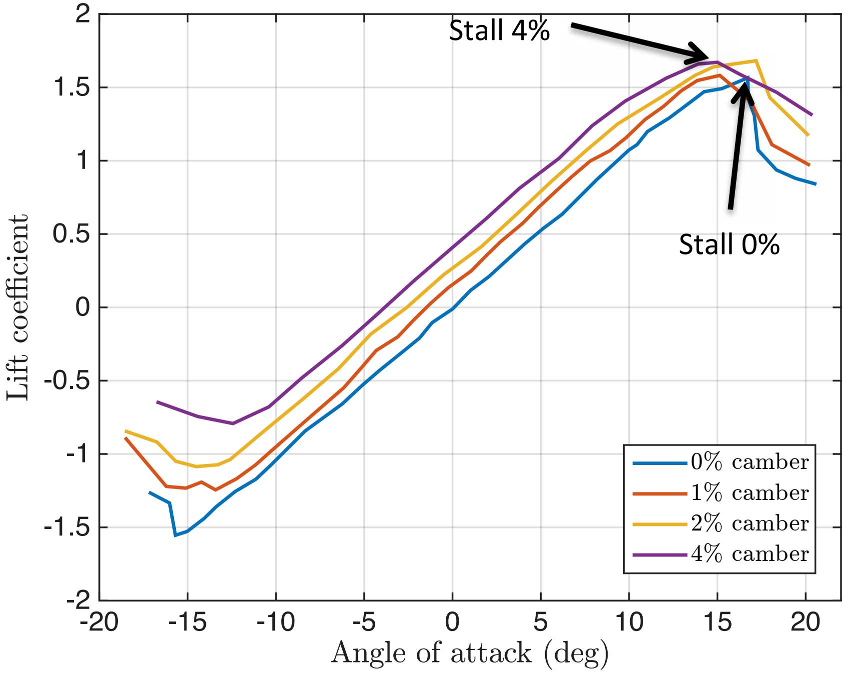
Highly cambered inboard

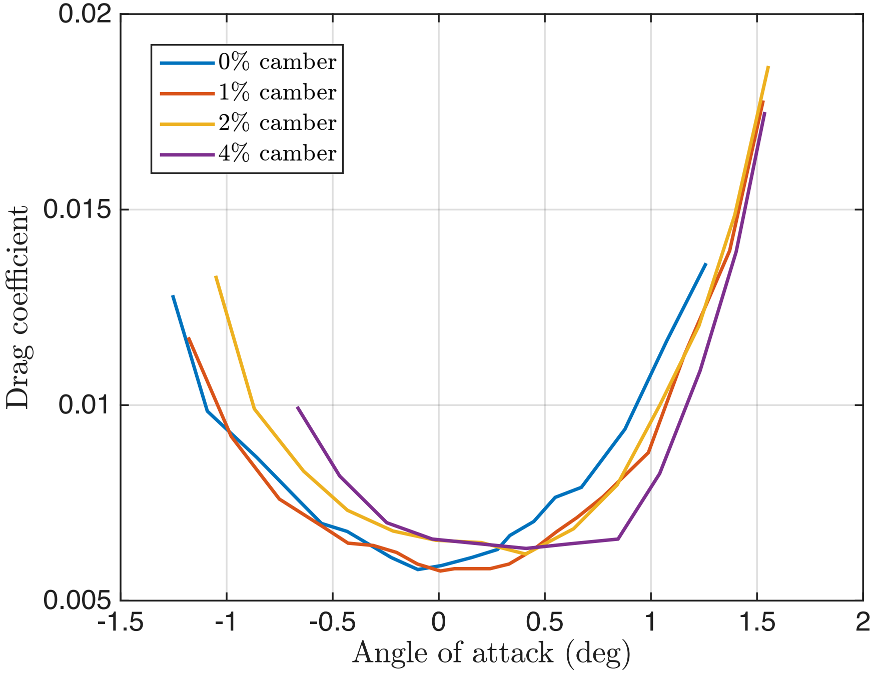






Effect of camber





- Effect of increasing camber on NACA 4-digit wing profiles.
  - Lift at 0º angle of attack increases
  - Angle of maximum lift decreases (i.e. stall occurs earlier)
  - Profile drag increases

Goose wing discussion – static conditions

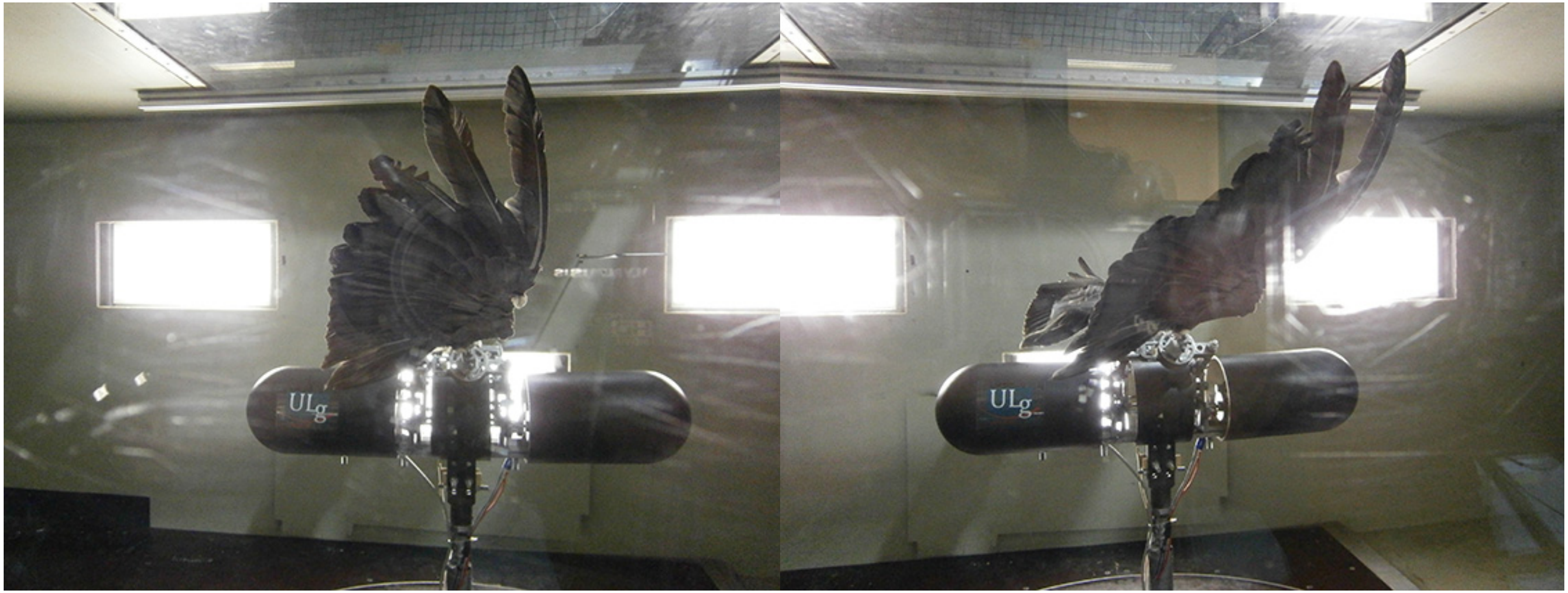
- Camber increases lift.
  - The wing inboard section is responsible mostly for lift generation, hence is it highly cambered.
- The outboard section of the wing is responsible mostly for thrust generation, it does not need to be highly cambered.
- Taper and twist reduced drag in static wings.
  - Outboard section highly tapered and twisted.
  - The twist is active: the feathers deform under the effect of the airflow.

Static wing deformation under airflow

- Bird wing at extreme angle of attack deforms as the airspeed is increased.
- Similar phenomena at smaller angles of attack; the magnitude of the deformation is smaller.
- The pitch angle on the outboard section is lower than on the inboard section.
- It’s not necessarily the case at the tip because the first primary deforms more than the others.

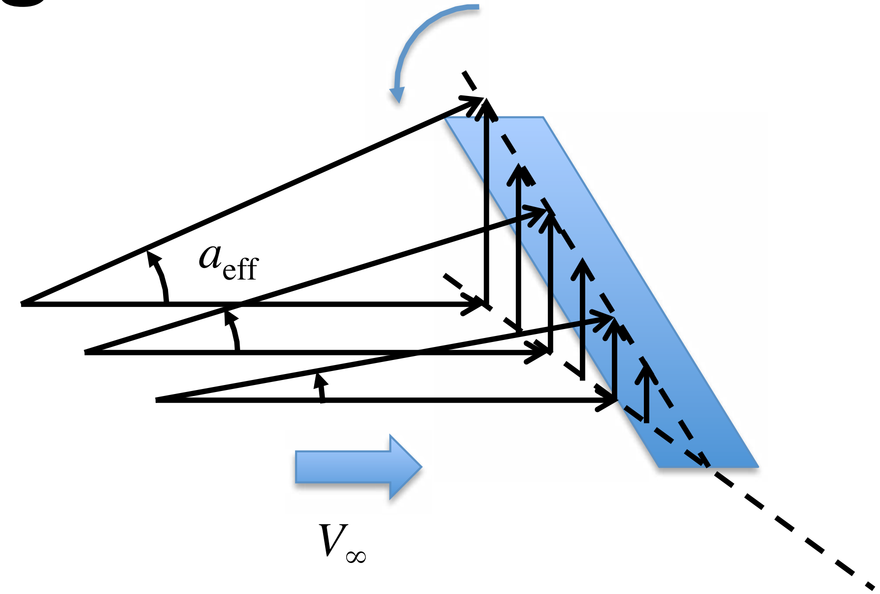
Primaries

- Two photos of goose wings in the wind tunnel.
- The first two primaries bend up much more than the others.



Effective angle of attack

- The wing is flapping down.
- It sees two flow components:
  - The free stream, constant along the span.
  - The upwash due to the flapping motion, varying linearly along the span.
  - The effective angle of attack is the vector addition of these two flow component.
- At the wingtip the upwash is strongest and therefore the effective angle of attack highest.
- Stall will occur first at the wingtip during the downstroke.

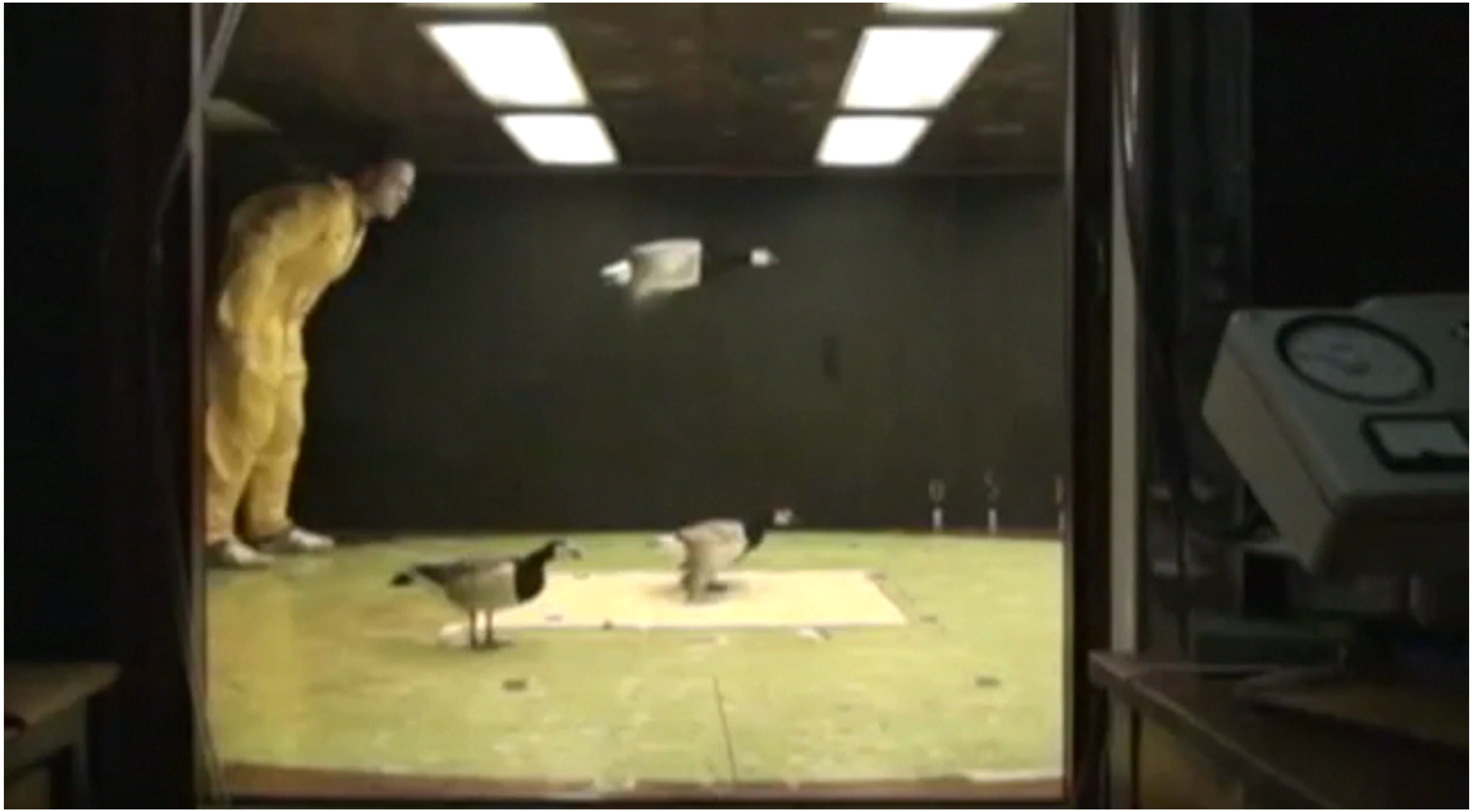


Goose wing discussion – flapping conditions

- Under flapping conditions, the outboard section has a very high effective angle of attack:
  - It risks flow separation.
  - The outboard wing twists down at the downstroke, reducing the total angle of attack and the risk of flow separation.
  - Taper and low camber also reduce the risk of flow separation.
  - The outboard sweep increases the risk of flow separation because it decreases the free-stream flow component seen by the wing.
  - The bird decreases sweep at the downstroke, i.e. moves the wing forward.

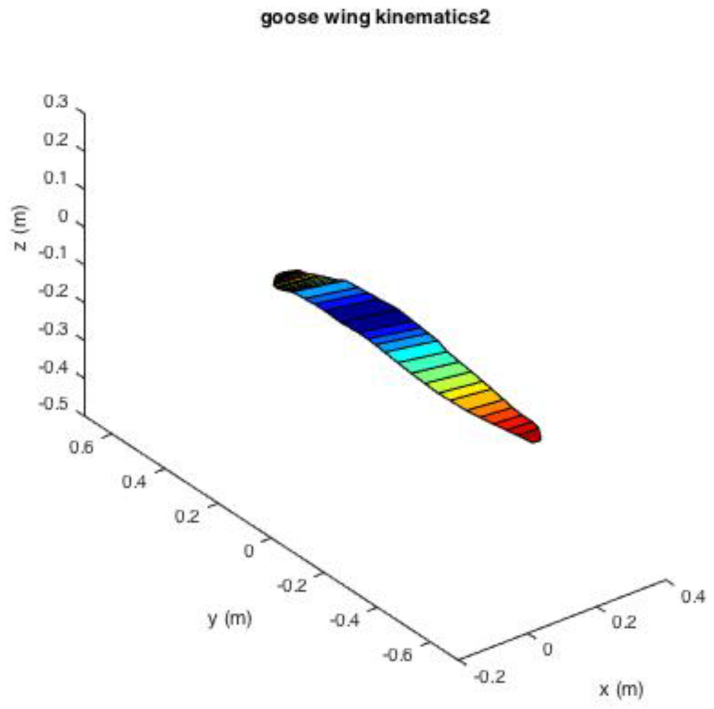
Bird flapping kinematics

- Experiment at the University of Manchester in 2007.



Observation on kinematics

- As the downstroke begins:
  - The wingtip moves forward, reducing sweep and increasing the magnitude of the horizontal flow component.
  - The wingtip twists downwards, reducing the local pitch angle.
- Both measures are designed to ensure that stall does not occur.



Digitised flapping kinematics from goose videos. V_∞=16m/s.

More on the experiments

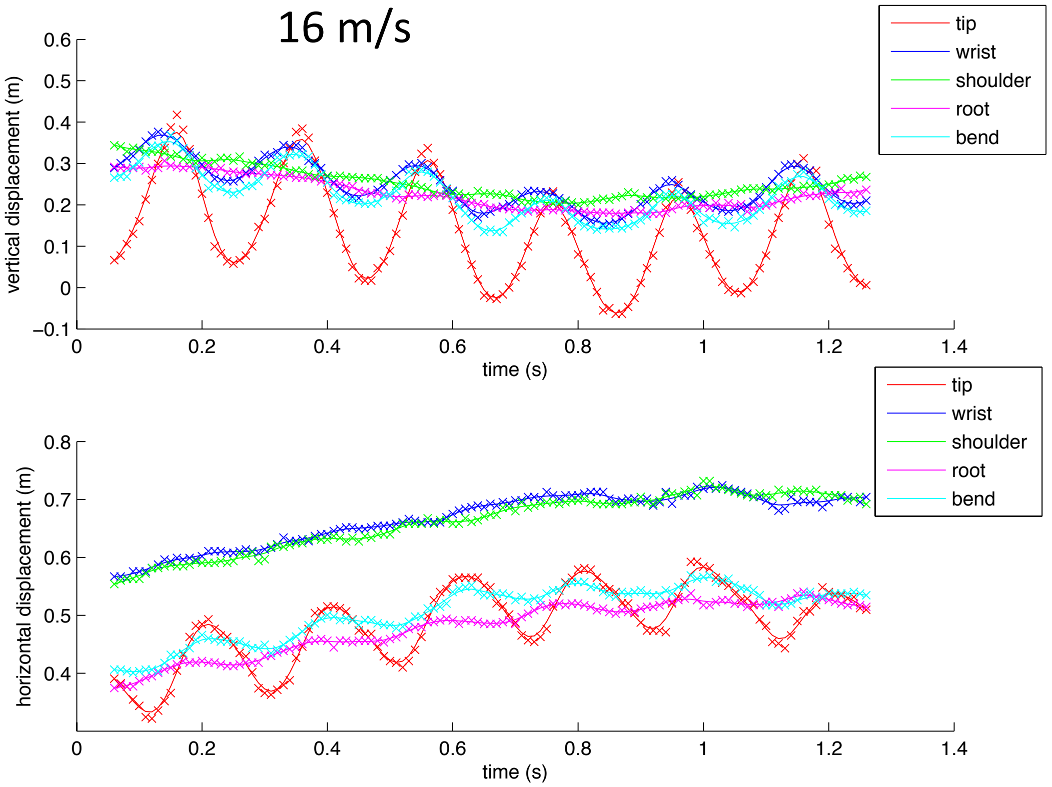
- Three barnacle geese were trained to fly in the wind tunnel and filmed.
- They flew at wind tunnel airspeeds of 14, 16 and 18m/s.
- Video was collected at 100 fps. All filming was carried out from the side. Over 60 videos in total.
- Several videos were digitized using Tracker 3.10 by Open Source Physics:
  - Five videos for 14 m/s
  - Four videos for 16 m/s
  - Five videos for 18 m/s

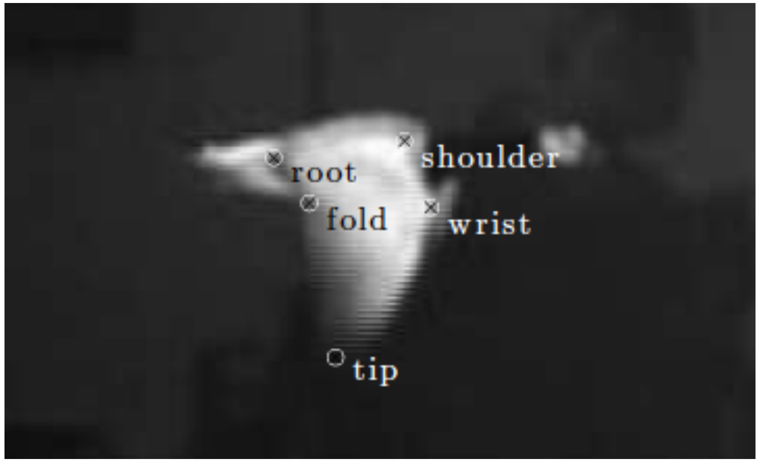
Reconstruction of wing kinematics

- In each video, five anchor points on the wing were tracked for five complete wing beats:
  - wing tip, wrist joint, shoulder joint, wing root trailing edge bend
- The video footage only provided data in two dimensions.
- Photographs of the planform of a goose wing were used to reconstruct the third direction.
- The wing was assumed to flap as two rigid sections:
  - the inboard wing, hinging around the body
  - the outboard wing, hinging directly behind the wrist joint

Measured wing kinematics

16 m/s



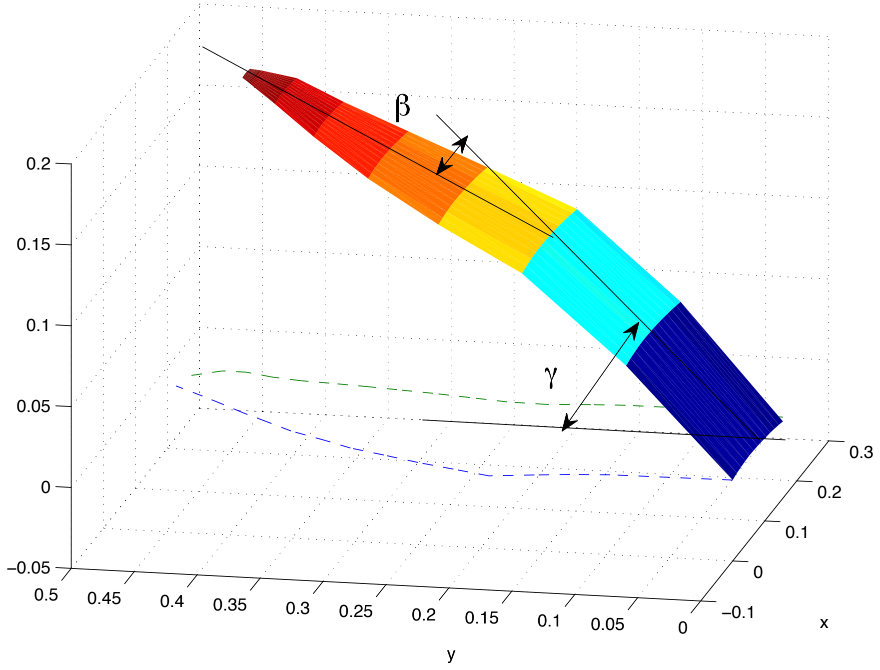


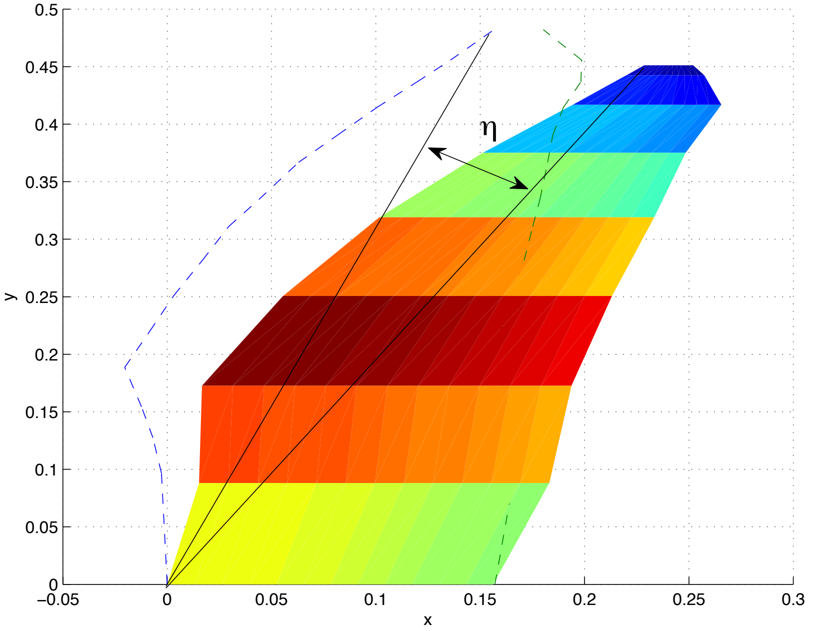
Mean values

Airspeed (m/s)	Frequency (Hz)	Wingbeat amplitude (m)
14	5.15	0.50
16	5.02	0.45
18	4.94	0.51

Simplified kinematic modeling

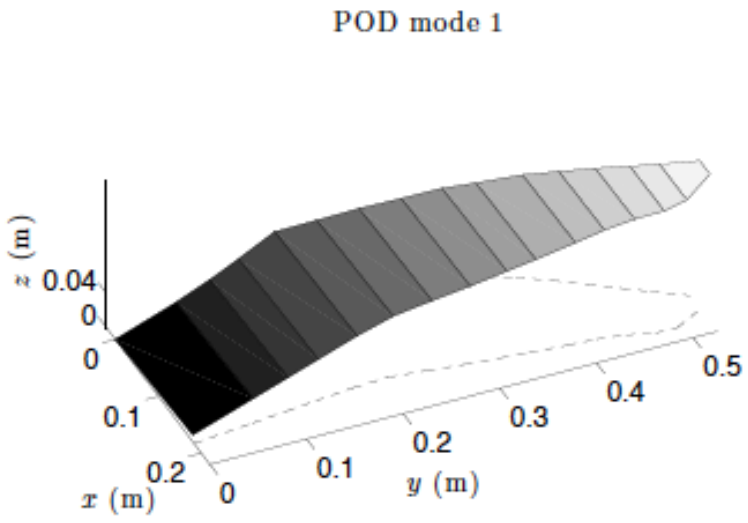
- The wing motion was simplified using three angles:
  - Flap, pitch, bend and lag



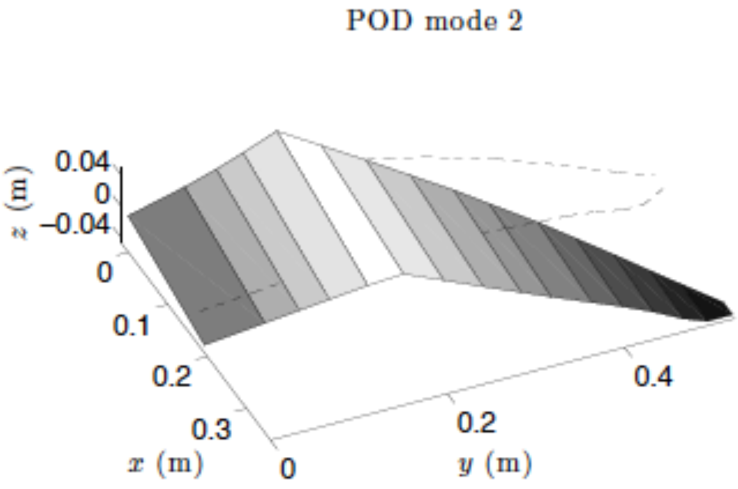


Mode shapes

- After applying Proper Orthogonal Decomposition it was found that all wing motion is a superposition of two mode shapes:
  - A flapping mode.
  - A bending and lagging mode.



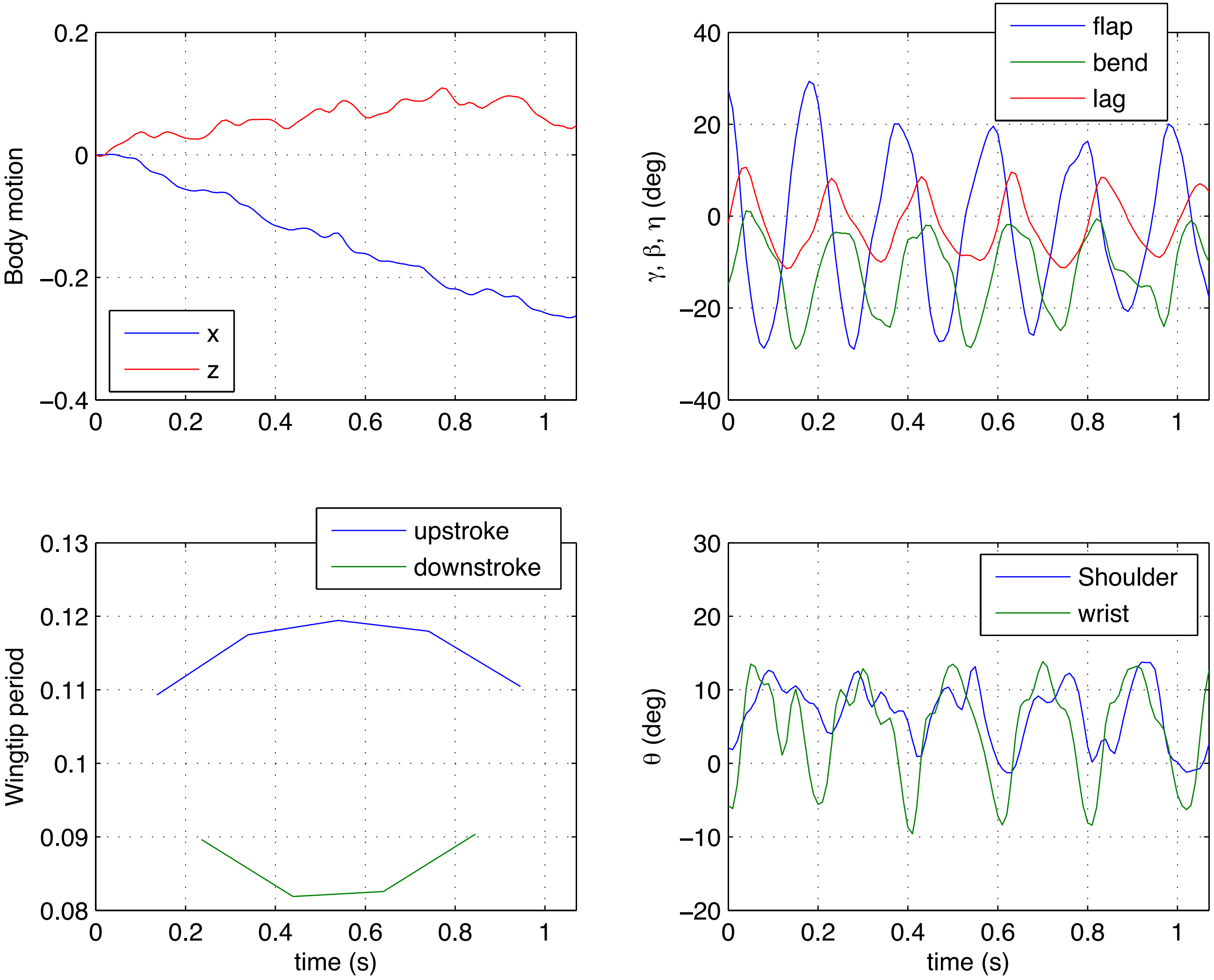
(a) Mode 1



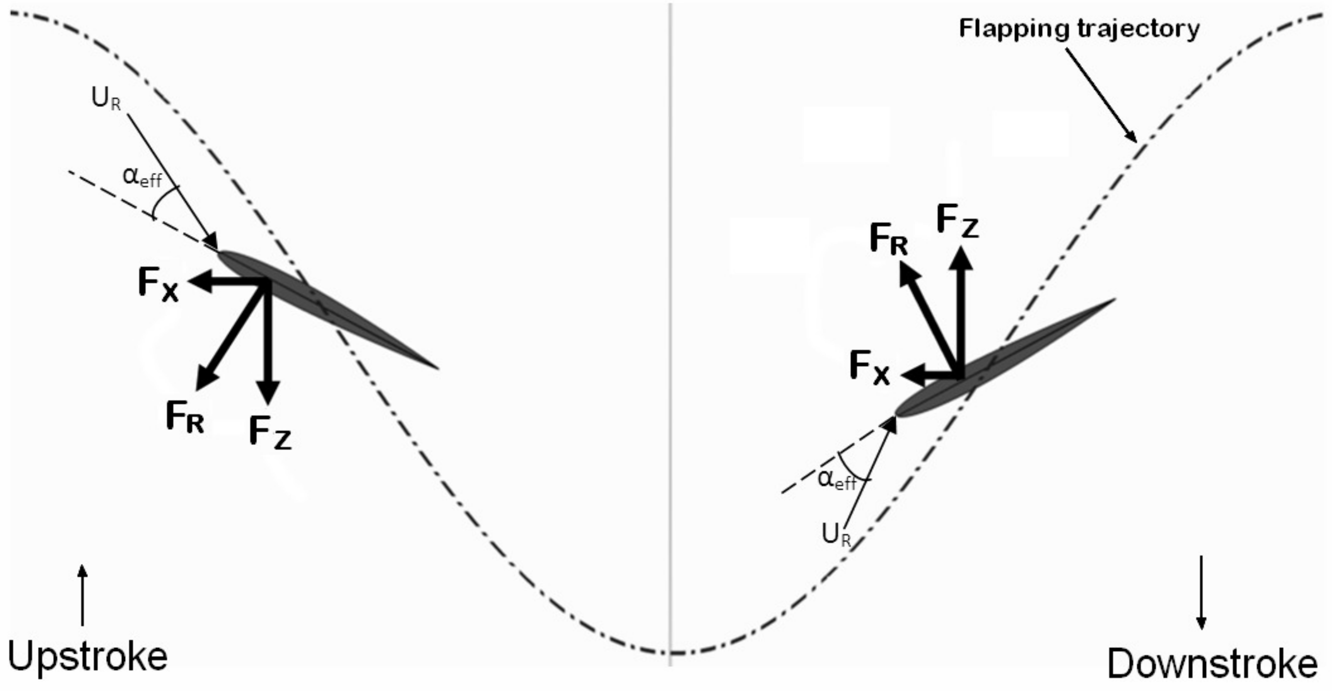
(b) Mode 2

Video 5 at 18 m/s

- In this video the bird is advancing quickly, i.e. generating a lot of thrust.
- The period of the downstroke is much shorter than that of the upstroke.
- The pitch angle at the wingtip is:
  - Negative during the downstroke
  - Positive during the upstroke.
- The pitch angle prevents flow separation but also optimises thrust production.

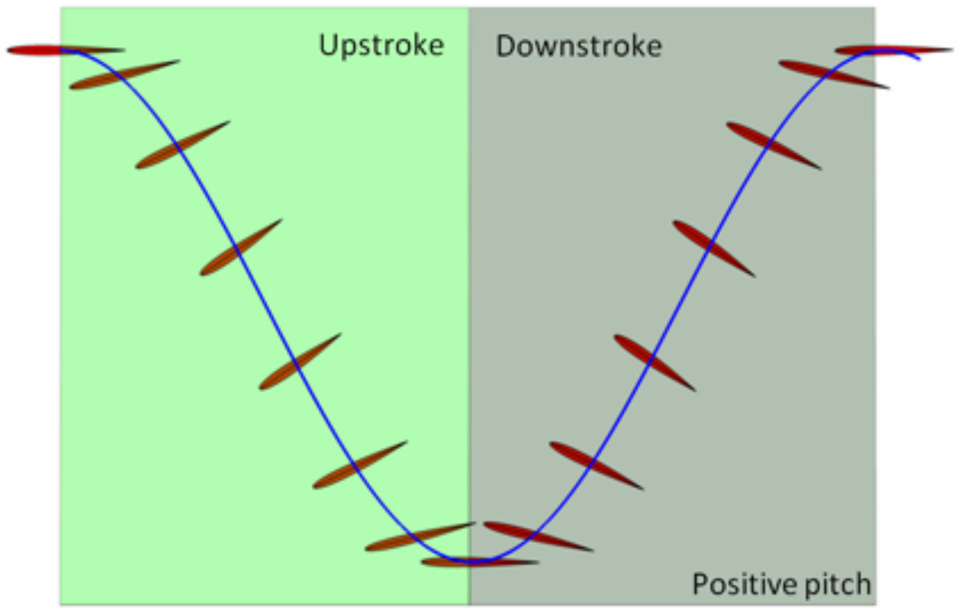


Knoller-Betz effect

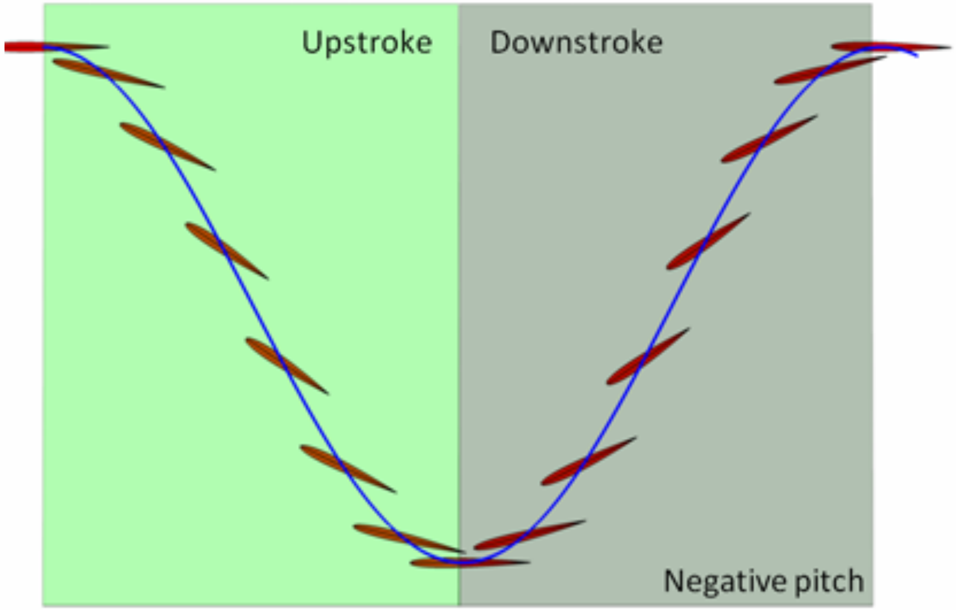


- The wingtip produces thrust throughout the cycle:
  - At the downstroke the pitch angle is negative and the resultant force is tilted forward.
  - At the upstroke the pitch angle is positive and the resultant force is tilted forward.
- This type of kinematics is known as pitch-leading.

Pitch lagging vs pitch leading



Pitch lagging



Pitch leading

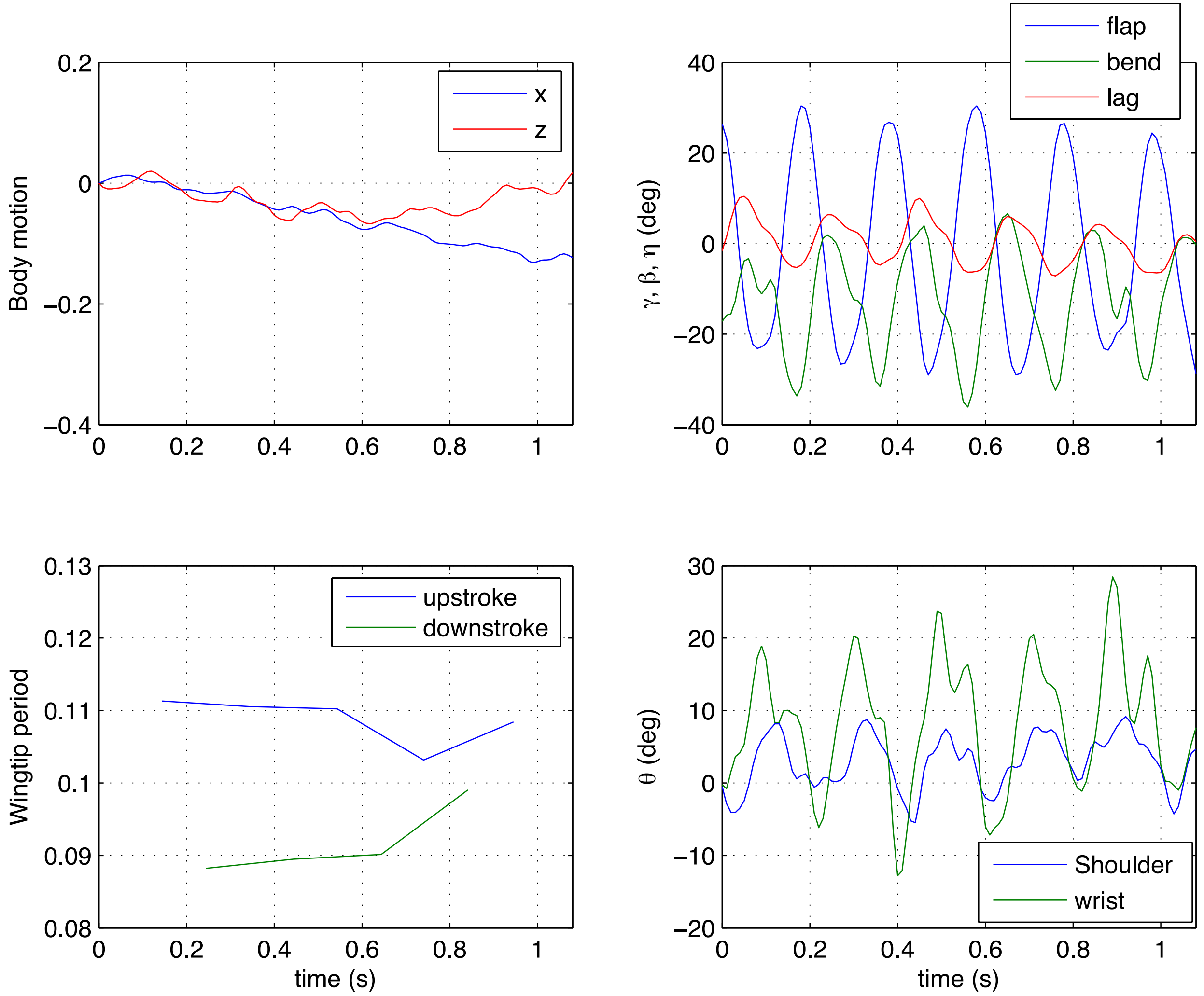
- Pitch lagging: when the wind starts flapping down, the pitch starts increasing.
- Pitch leading: when the wind starts flapping down, the pitch starts decreasing.
- In both cases the phase difference between pitch and flap is 90^o.

Theory and observation

- The pitch angle observations from the goose flights show that the phase difference between the pitch and flap angles is not 90°, it is less than 90°.
- This mismatch between theory and observation may be:
    - Error in observation, due to the low resolution of the videos.
    - A true phenomenon, due to the flexibility of the wing and specifically the primaries.
- The videos seem to show that the wingtip feathers assume a very negative pitch angle right near the start of the downstroke.
- The pitch angle increases throughout the downstroke to the point where it is already positive at the start of the upstroke.
- It becomes even more positive during the upstroke, before decreasing again to negative.
- This phenomenon may be localised on the leading primaries. We have already shown that the first primary bends more than the others.

Video 1 at 18 m/s

- In this video the bird first looses height, then climbs back up.
- The period of the downstroke is still shorter than that of the upstroke.
- As the bird climbs, the duration of the upstroke decreases and that of the downstroke increases.
- Climb is accompanied by longer downstrokes.
- The bulk of the lift and thrust are generated during the donwstroke.
- The pitch angle at the tip is higher than in the previous example.



Role of kinematics

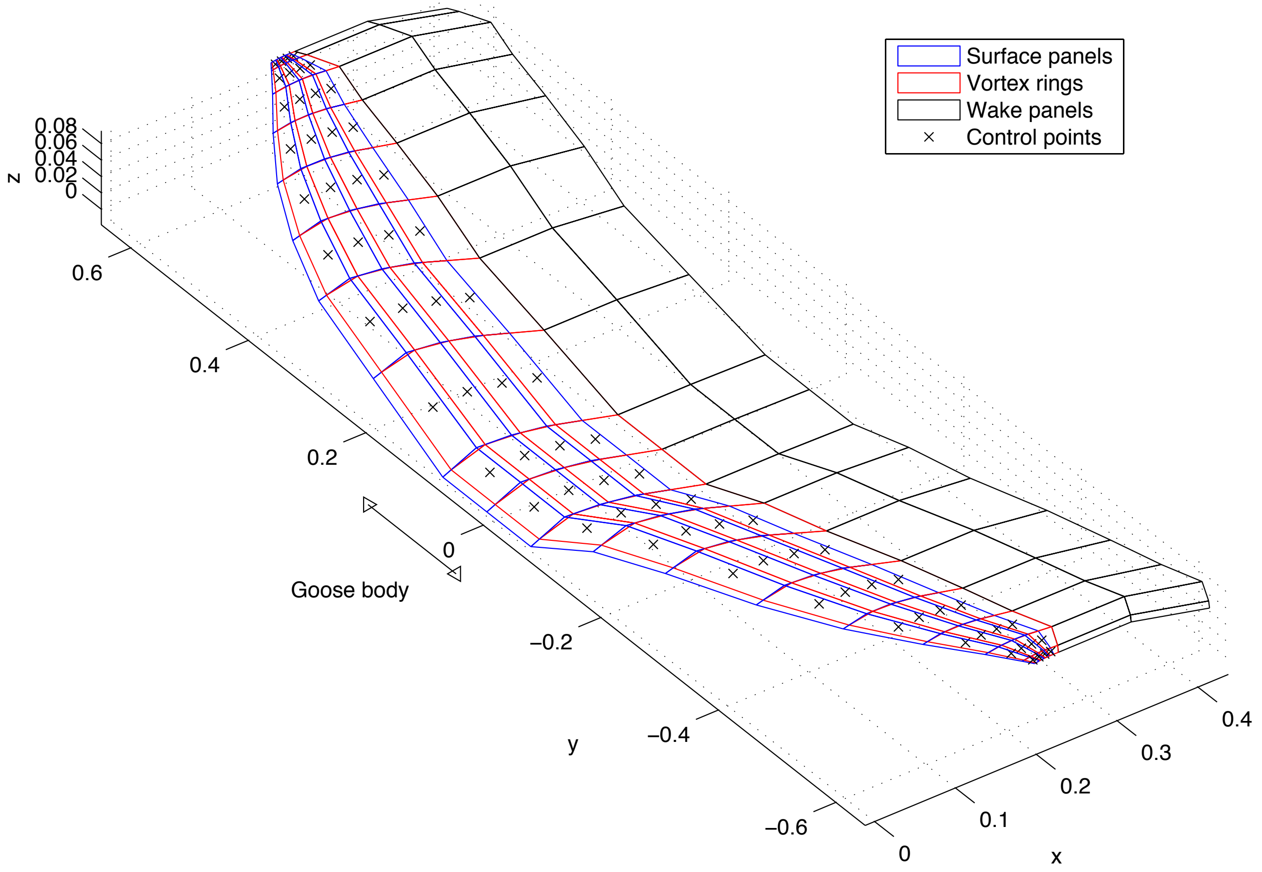
- The kinematic observations have shown the following tendencies:
- More thrust is generated by:
  - Shorter downstrokes
  - Higher pitch angles
- More lift is generated by:
  - Longer downstrokes
  - Lower pitch angles.
- The thrust and lift are inferred by the movement of the goose's body, the are not measured.

Estimating the lift and thrust

- The aerodynamic loads acting on the wings are modelled using a 3D unsteady Vortex Lattice Method.
- The kinematics input into the simulations is the one measured in every video.
- The simulations are calibrated in order to give the same body motion as the video.
- Then we can suppose that the simulated lift and drag forces reflect the ones generated by the wings of the bird in every video.

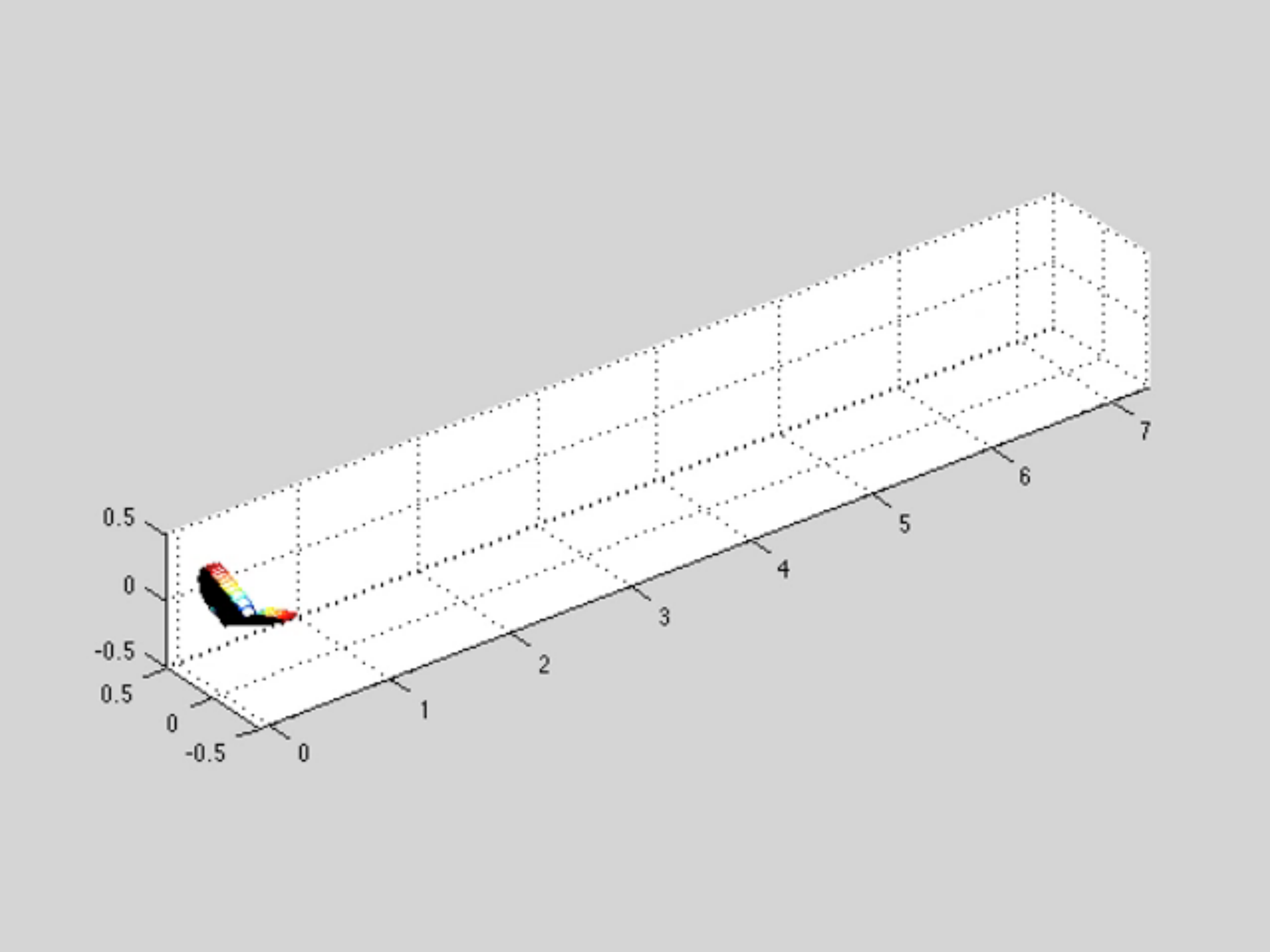
Vortex lattice modeling

- The wing is modeled as a flat cambered surface that moves with the measured wing kinematics.
- The surface is divided into chordwise and spanwise panels on which we impose boundary conditions.
- The wake behind the wing is also modeled.



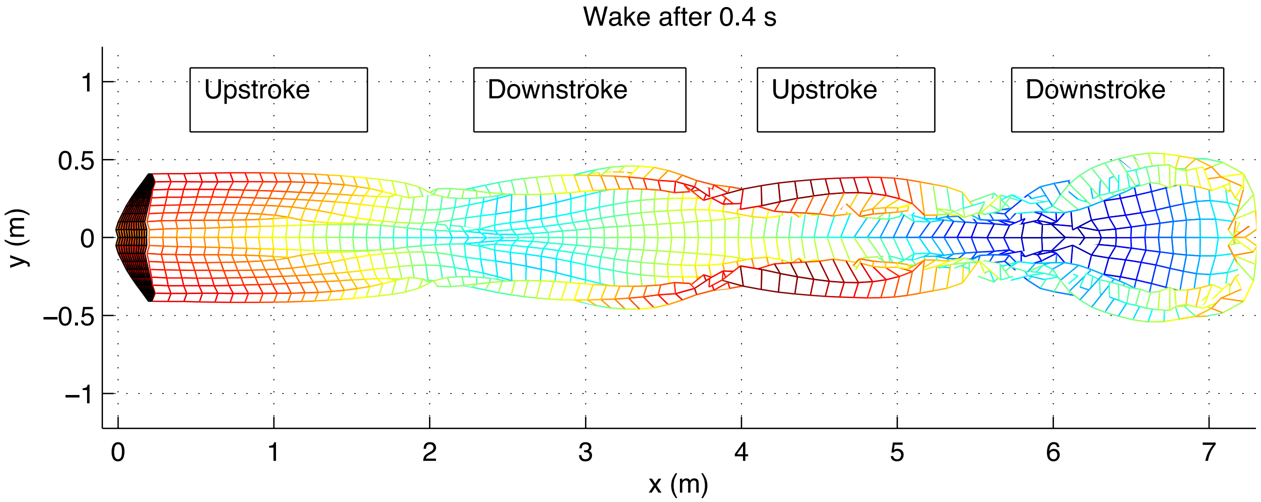
Wake shape

- Unsteady wake shape at 18 m/s
- Wake rolls upwards when the wingtip produces lift and vice versa

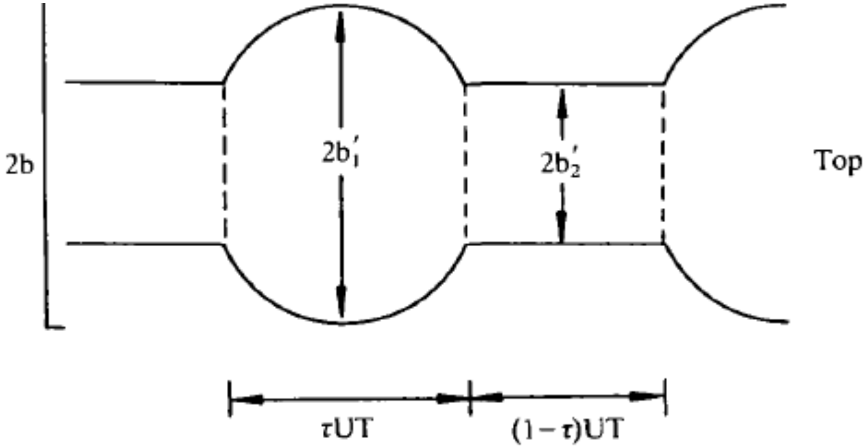


Concertina wake

- The simulated wake shape agrees with experimental observations by Spedding



Spedding, The wake of a kestrel in flapping flight, Journal of experimental biology, 127, 1987



Continuous ring gate

Weight and drag

- The mass of the goose was measured at 1.79 Kg (average value for a migrating goose)
- The drag coefficient of the body was taken to be 0.1 based on the frontal area (Pennycuick et al)
- Equations of motion for the centre of gravity were setup and solved in the horizontal and vertical directions.

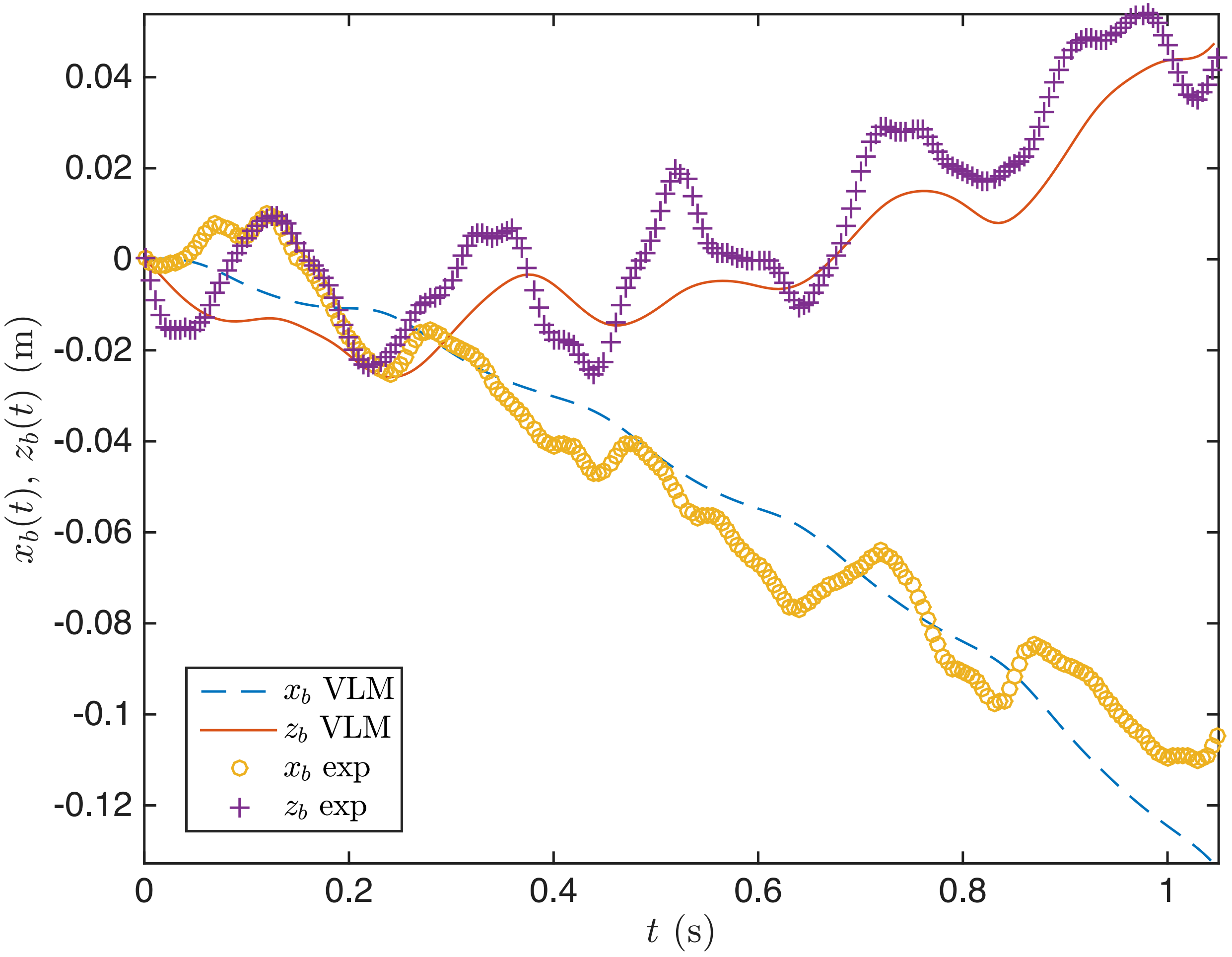
Centre of Gravity position

The centre of gravity is constantly moving horizontally and vertically, as seen in the goose videos.

The vertical displacement amplitude is of the order of 5 cm. Most of the climb occurs at the last part of the motion.

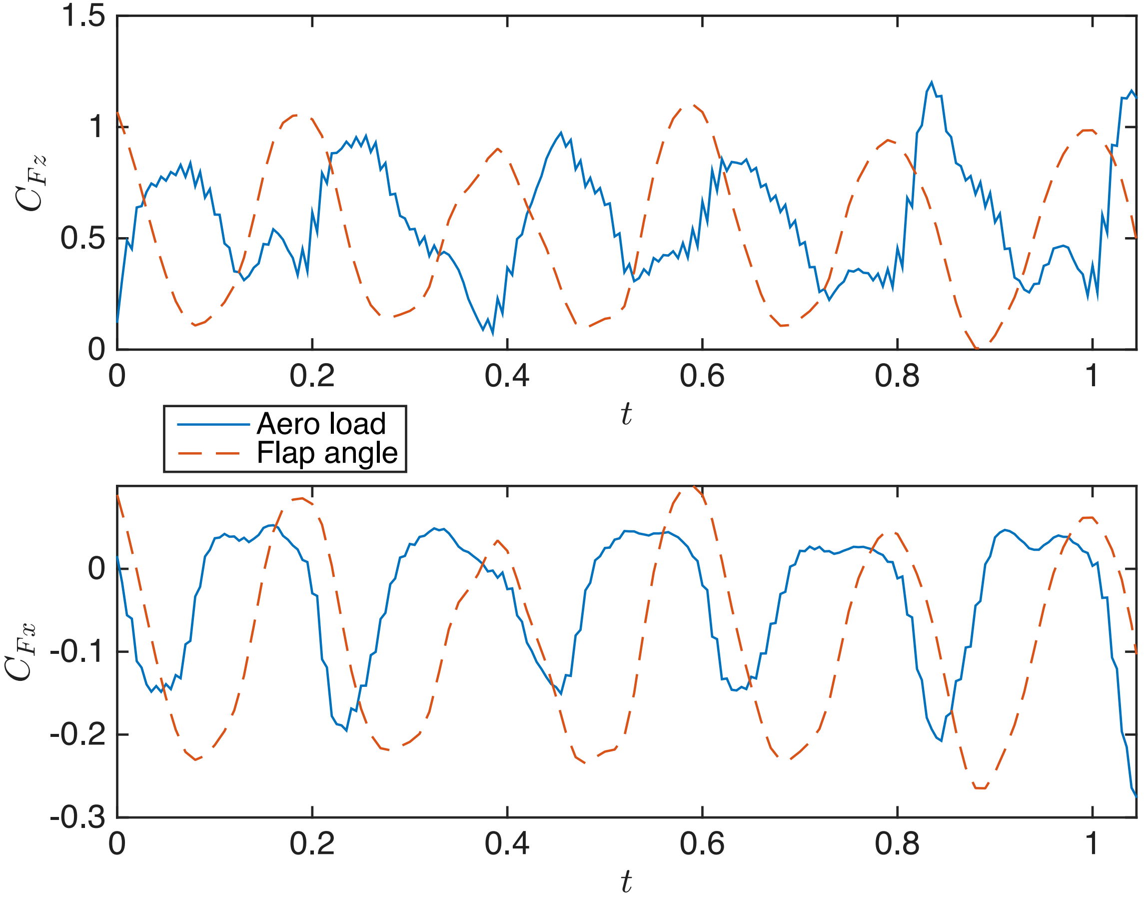
The horizontal displacement is of the order of 10 cm.

The simulation matches the movement of the CG very well.



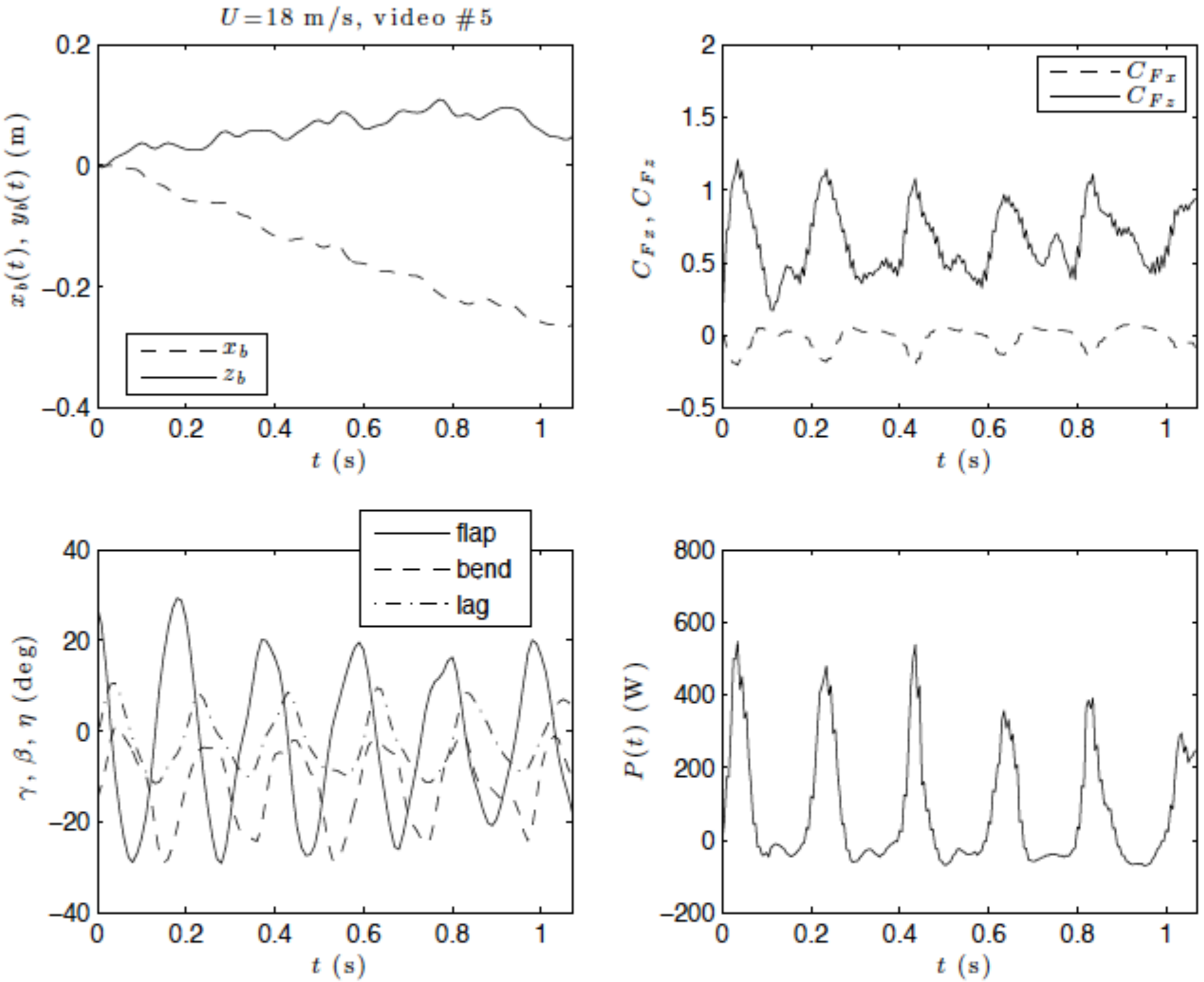
Corresponding aerodynamic loads

- The estimated aerodynamic loads show that:
  - The lift peaks increase towards the end of the motion when the bird starts climbing.
  - The thrust peaks also increase towards the end of the motion.
- As the bird climbs it looses forward kinetic energy.
- In order to keep advancing, it must increase the thrust.



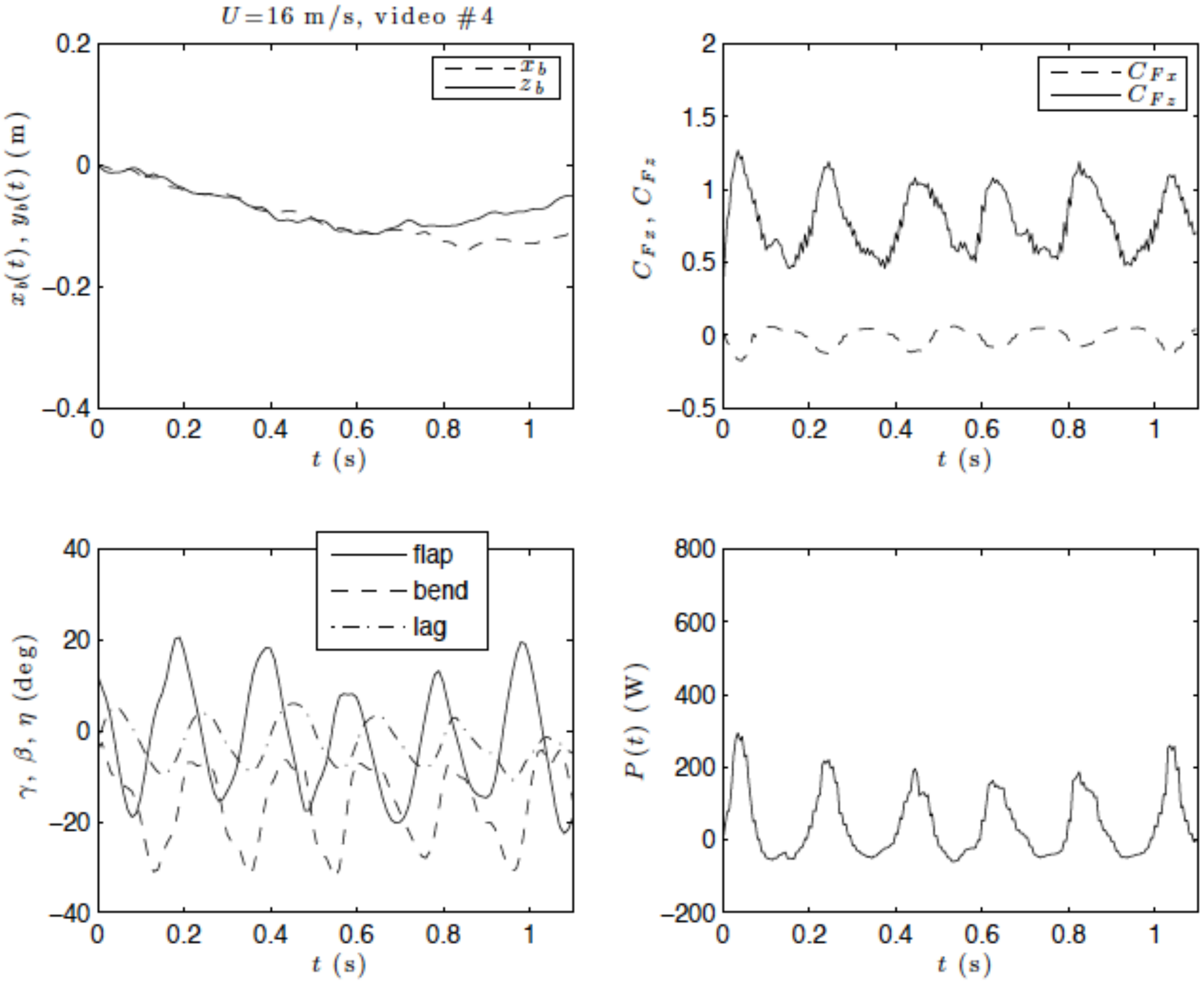
Power

- Here the bird climbs at first but then eases off.
- The estimated aerodynamic loads can be used to estimate the aerodynamic power.
- It is clear that the peak power drops over the last three flaps.



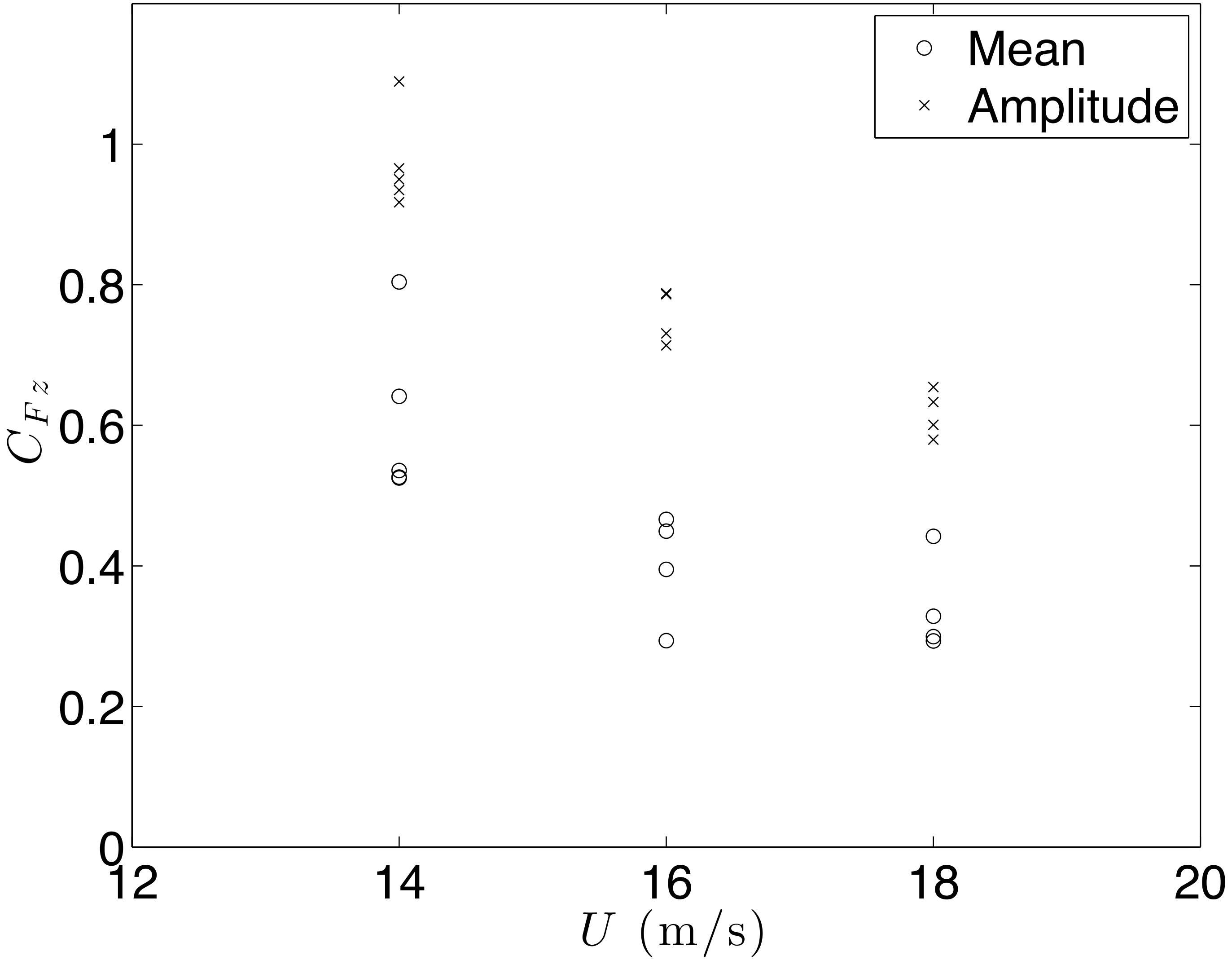
Another example

- In this example the bird first descends then climbs.
- The aerodynamic power first decreases then increases.



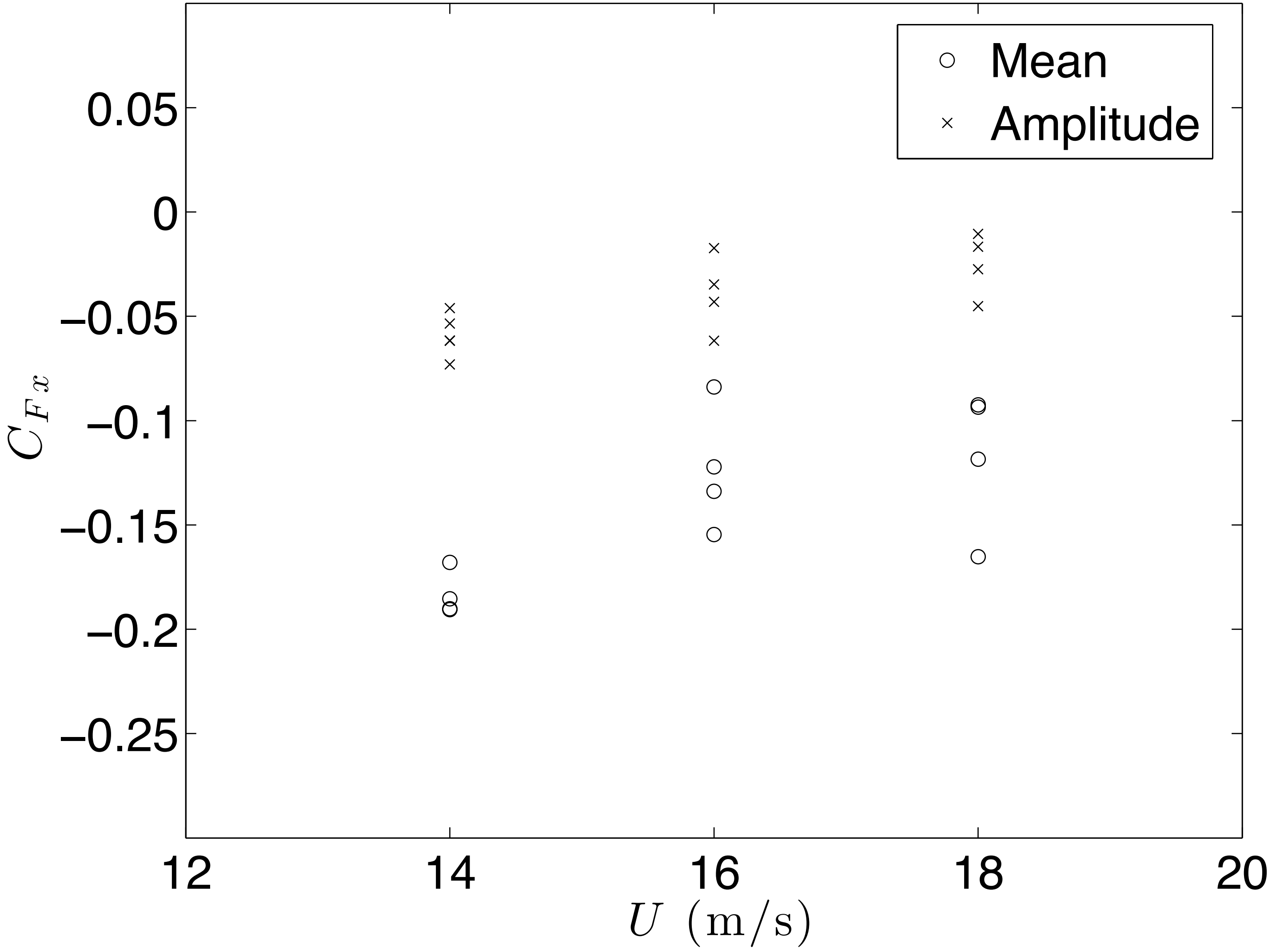
Lift vs Airspeed

- Root Mean Square lift coefficient for all flights at all airspeeds.
- The lift coefficient decreases significantly with airspeed.
- This is normal: the same wing with the same lift coefficient produces more lift at higher airspeeds.



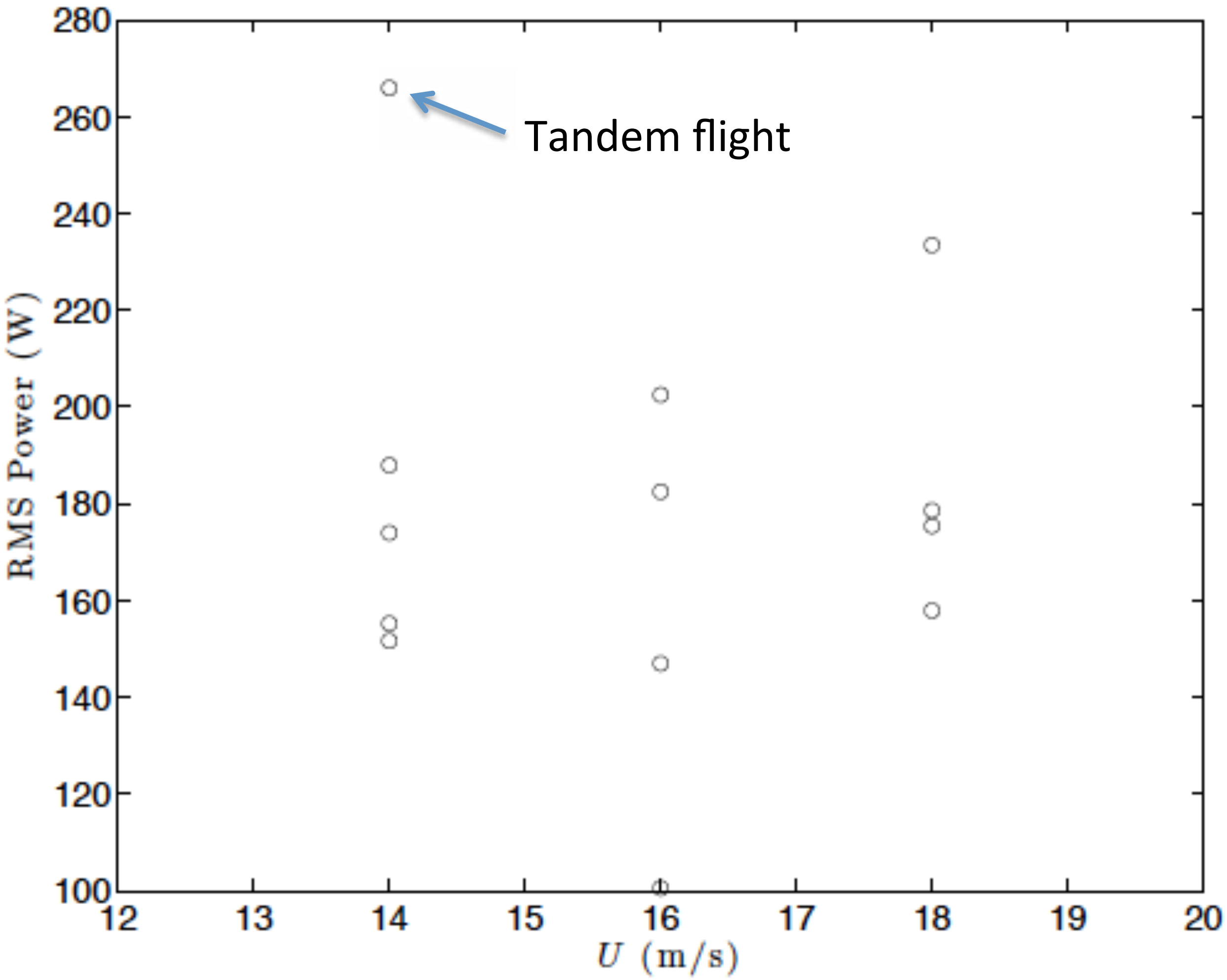
Thrust vs Airspeed

- RMS thrust for all flights at all airspeeds.
- The thrust coefficient increases with airspeed.
- This is normal, parasite drag increases with airspeed and therefore more thrust is needed.



Power vs Airspeed

- Root-mean-square aerodynamic power for all cases analyzed.
- There is a clear tendency for power to increase with airspeed.
- The rogue point at 14 m/s is a tandem flight.



Conclusions

- There are some clear tendencies in the data:
  - The total flap frequency is nearly constant.
  - Downstroke is always shorter than upstroke.
  - Lengthening of the downstroke produces more lift.
  - Shortening of the donwstroke produces more thrust.
  - As the airspeed increase, so does the difference between the durations of the upstroke and downstroke (downstroke becomes shorter).
  - Aerodynamic power peaks at the downstroke. The peak value can be anything between 200W and 600W.
  - Power increases with airspeed.
  - The combined kinematics are responsible for flight efficiency.

Further work

- The experiments show that feather flexibility is very important to the aerodynamic loads.
  - It is not yet clear how the two affect each other.
  - Several experiments have been carried out to try to improve our understanding of this issue.