Flapping flight aerodynamics for flying animals

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Introduction

- Most research into the aerodynamics of flying animals is based on aircraft aerodynamics
- Aircraft have rigid wings, therefore such research is mostly suited to the study of the gliding flight of animals.
- However, many species spend more time flapping than gliding. Some species don't glide at all.
- Very little research has been carried out on flapping flight to date.

Flapping flight

- In the past flapping flight received very little attention from aeronautical engineers. Aircraft don't flap their wings:
  - They use rigid wings to create lift
  - Propellers, jet engines, rockets etc provide the thrust
- However, flapping flight has been the subject of some recent interest.
- The target applications are:
  - Ornithopters: medium-sized unmanned aircraft (UAV) that flap their wings in the manner of a bird
  - Entomopters: small unmanned aircraft that flap their wings in the manner of an insect

Examples of flapping aircraft

University of Toronto Ornithopter

Festo SmartBird

Erich von Holst
ornithopters

Flapping research

- If the application of flapping flight to engineering is to go further there must be extensive research.
- Several aspects are of importance, such as:
  - Aerodynamics
  - Flight stability and control
  - Actuation
  - Power sources
- Biological prototypes can help to achieve improvements on all these aspects (SmartBird inspired by herring gull).

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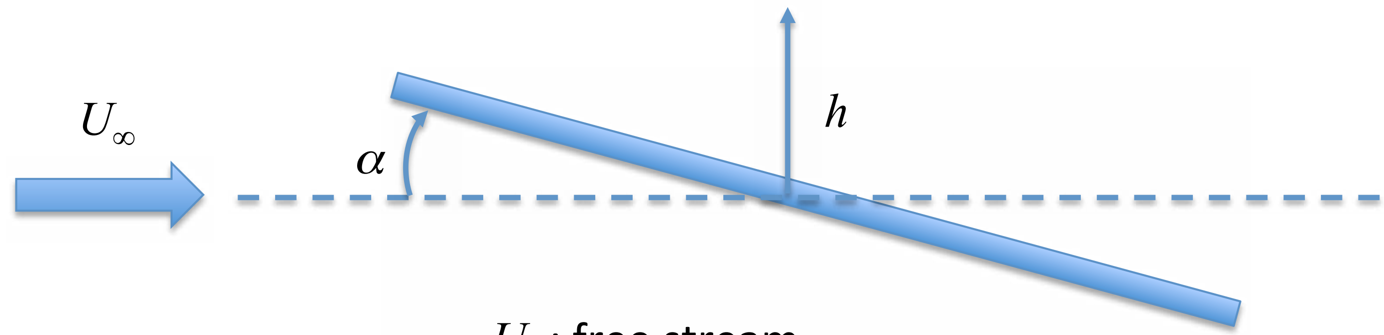
Aerodynamic research tools

- The aerodynamic research tools that can be used for flapping flight research are the usual:
  - Observation of biological examples
  - Aerodynamic theory, including simulation
  - Wind tunnel experiments
  - Flight testing
- In this presentation we will concentrate on aerodynamic simulation and wind tunnel testing.

Flapping flight aerodynamic theory

- Flapping flight theory was first developed in the 1920s and 1930s by Von Karman, Garrick and others.
- The works concerned two-dimensional flat plates that can oscillate in pitch and plunge.



U_∞: free stream
α: pitch angle
h: plunge displacement

The 50% limit

- Garrick showed that a purely plunging flat plate can produce thrust.
- However, the maximum efficiency of this thrust production is 50%. This is very low compared to propeller efficiency (closer to 90%).
- Combined pitching and plunging can yield higher but also lower efficiency, depending on the choice of parameters.
- As plunging is the 2D equivalent of flapping, the 50% limit was taken to meant that flapping flight is not very efficient.
- This statement, combined with additional flapping flight problems, such as actuation and power generation, meant that very little flapping research was carried out since then.

And yet they fly

- Animals can clearly fly very well and it is very unlikely that their efficiency is only 50%.
- Since the 1990s several researchers have studied the issue and concluded that combined pitching and plunging can yield efficiencies up to 90%.
- However, this work also suffered from the same limitation: it only considered attached 2D flow.
- The flow around flying birds is three-dimensional.
- Furthermore, birds don't necessarily hate separated flow. Only aeronautical engineers do.

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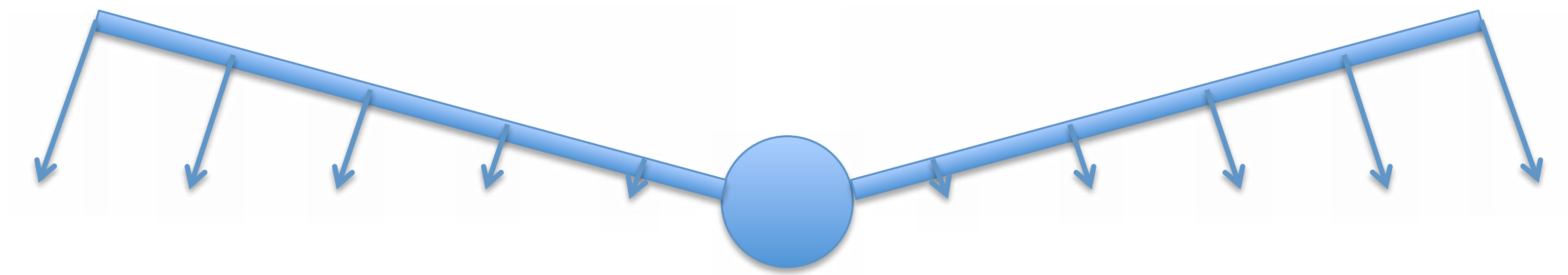
3D flow

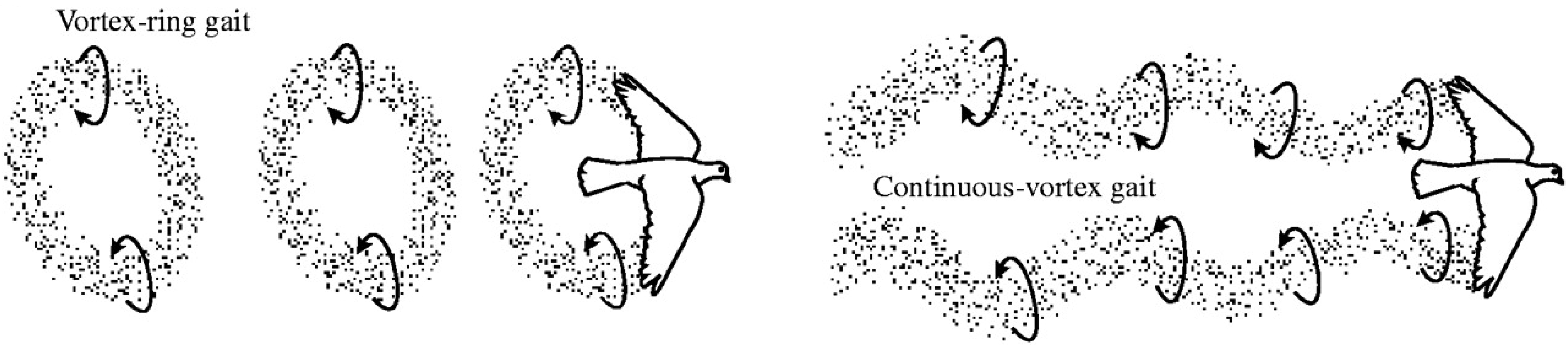
- In order to properly understand flapping flight, the 3D phenomenon must be considered.
- The first crucial difference between 2D and 3D flapping is that the plunging speed at the wingtip is much higher than that at the wing root.



- If the inboard section doesn't plunge much, it can't produce much thrust either.
- It is logical to suggest that the inboard section of the wing produces mainly lift while the outboard section produces mainly thrust.

3D wake

- Another crucial difference between 2D and 3D flapping is the shape of the wake.
- For a static 3D wing, the wake consists mainly of two straight trailing vortices, extending from the wingtips backwards.
- Bird research has shown that flapping wing wakes can have different shapes, depending on the flapping gait.



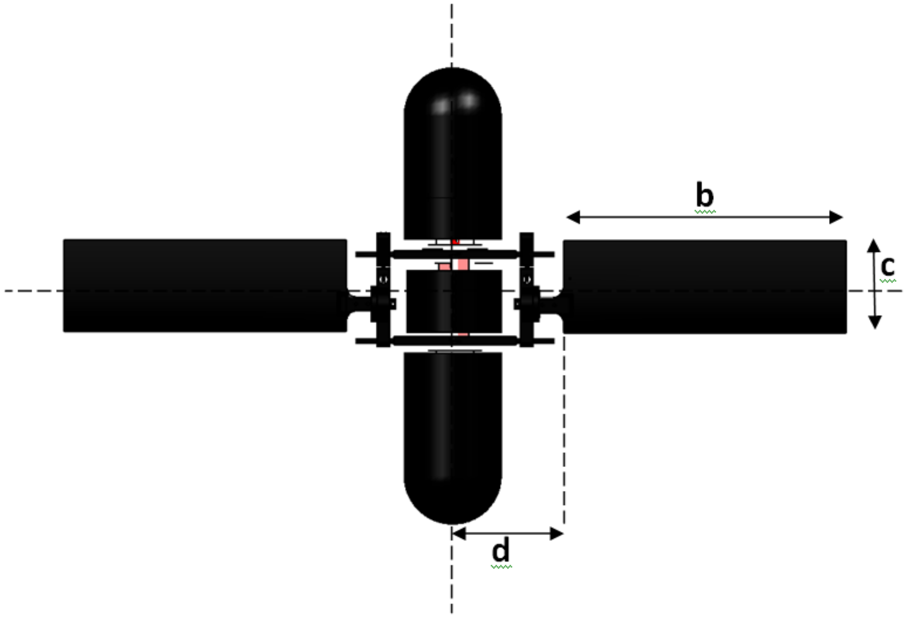
Better 3D flapping flow modeling

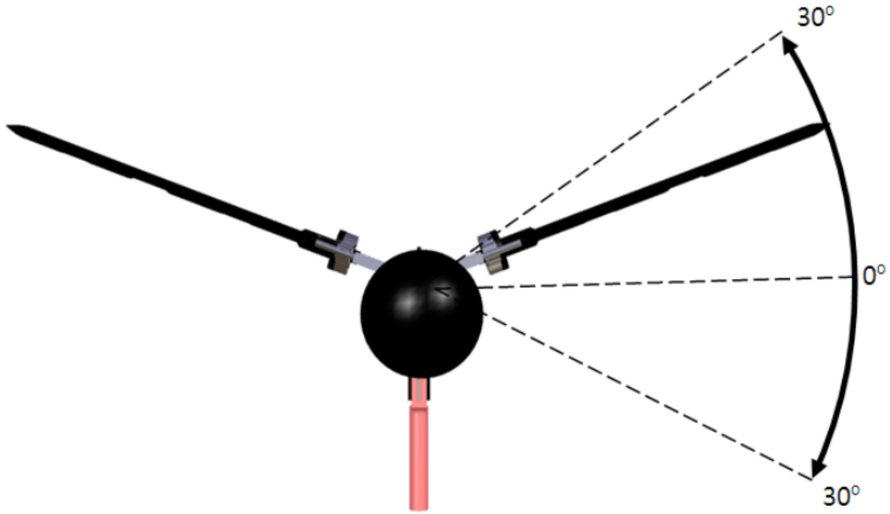
- In order to better predict the thrust and lift generated by flapping flight we need to develop better theoretical models
- Analytical models of 3D unsteady aerodynamics do not exist.
- Numerical models can be developed by borrowing from aeroelasticity:
  - Vortex lattice approach: The wing is modeled as a cambered plate without thickness
  - Source-doublet method: The wing can have thickness
- Experimental validation of these models is needed to demonstrate their validity and determine their limitations.

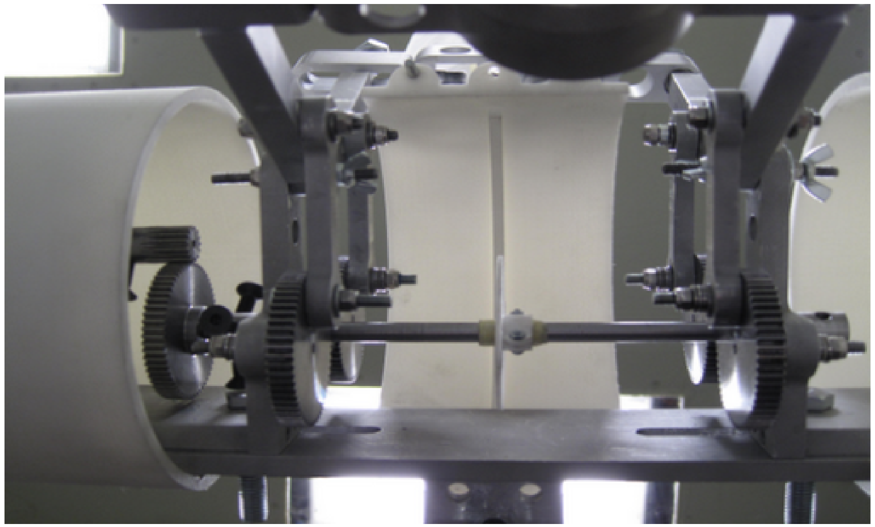
Project Frankenbird

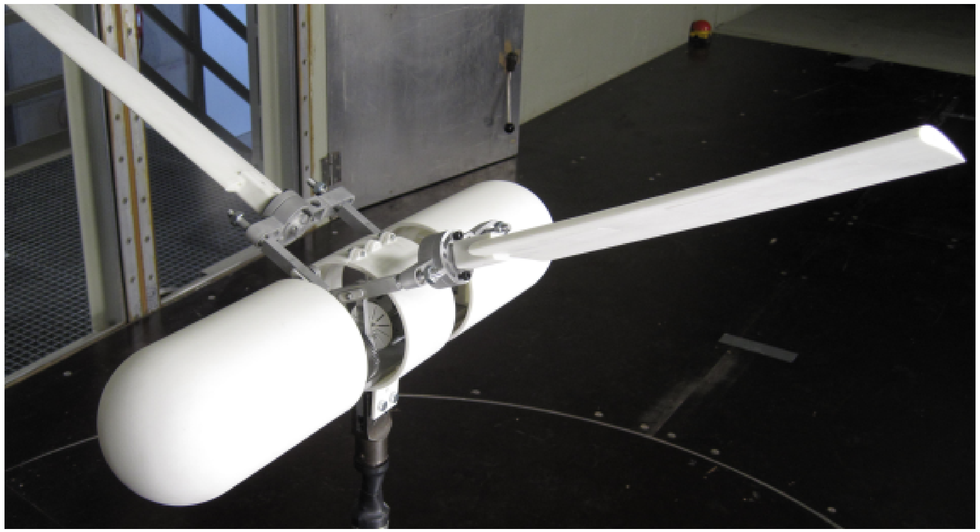
- We undertook project Frankenbird at the University of Liège in order to address these issues.
- Frankenbird is a robotic wind tunnel model that can both flap and pitch its wings.
- It is powered by a single electric motor turning a tandem dual crank mechanism.
- Any type of wing can be attached to the crank mechanism (can't be too long for the wind tunnel's working section or too heavy for the motor to move).
- The flapping wings are also modeled using the Vortex Lattice method. Comparisons between experiment and theory are carried out.

Frankenbird









Frankenbird details

- Its general specifications are consistent with a medium-sized bird such as a duck.
- The total wingspan is around 1.3m and the total aspect ratio is 8.6.
- The flap amplitude angle is ±30°.
- The default pitch amplitude is ±15° but can be increased.
- Driven by a single DC brushless motor that comes with a reduction gear of 5:1 ratio.
- Both the motor and controller are powered by 12Volt wet cell batteries (car batteries).

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Instrumentation

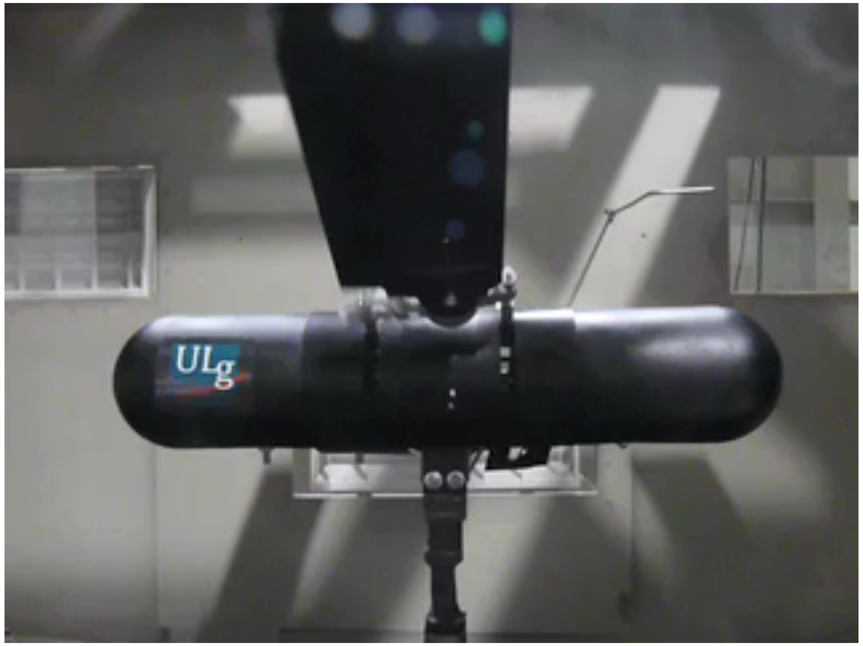
- Frankenbird has has the following internal sensors:
  - RPM sensor.
  - Instantaneous flap and pitch angle measurement sensors.
- The following external sensors are used:
  - Force sensors for the instantaneous lift, drag and sideforce.
  - Pressure sensor for the pressure distribution around wings with pressure tappings.
  - Particle Image Velocimetry flow visualization.
- A custom program Visual basic 6.0 for the control interface
- C-language program for the microcontroller that controls the DC motor and the rpm sensor.

Frankenbird in action

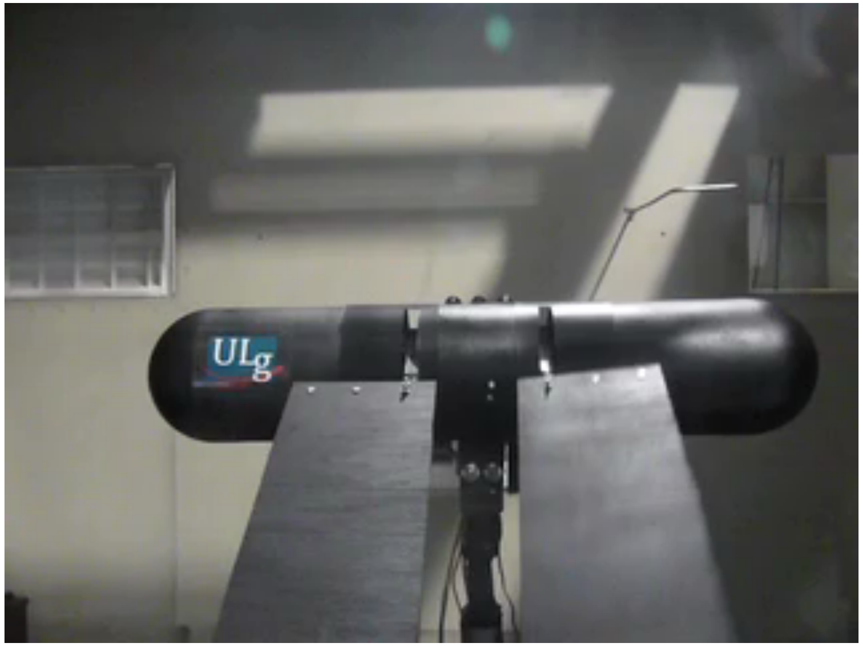
Pure flapping

Flapping and pitching

More action



Flapping and pitching with a lot of pitching



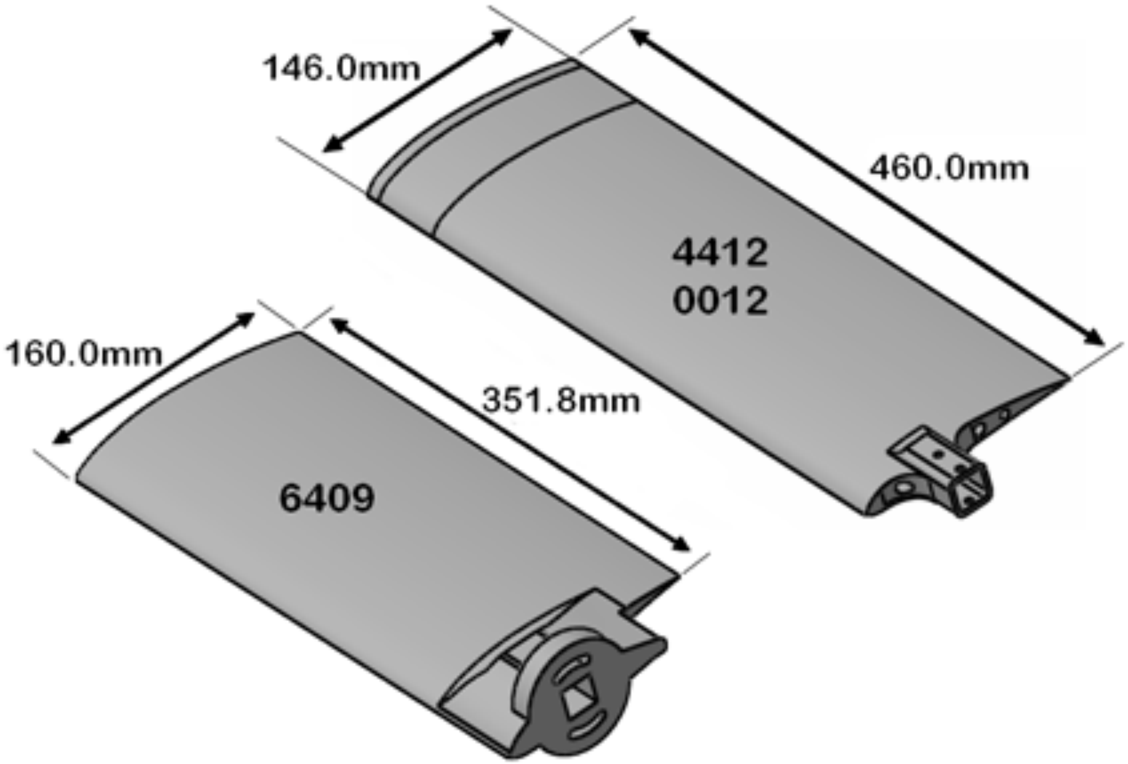
Tandem wings

Experiments carried out

- Four sets of experiments on four different types of wing (all rectangular):
  - Flat plate
  - NACA 0012
  - NACA 2412
  - NACA 6409
- Experimental parameters:
  - Wind tunnel airspeed
  - Flapping frequency
  - Flapping amplitude
  - Pitching amplitude
  - Phase difference between flapping and pitching

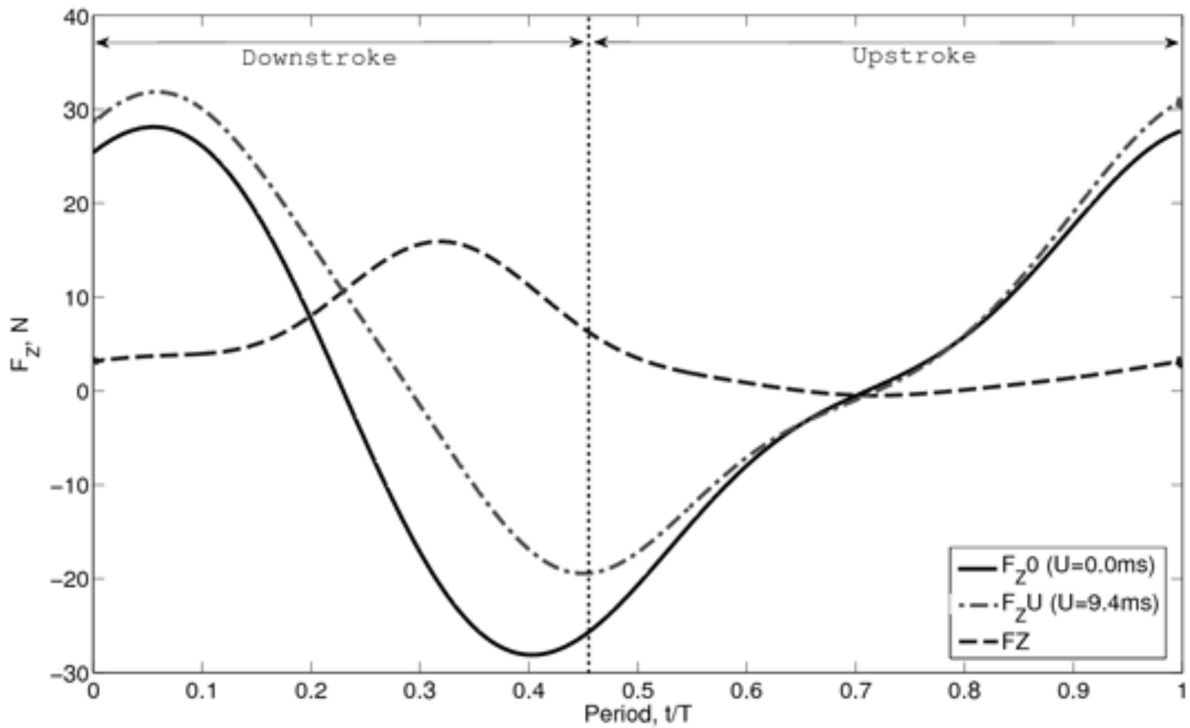
Wings used

- The NACA 6409 was shorter but with longer chord than the other two NACA wings.
- All three were rectangular, straight, untapered and untwisted



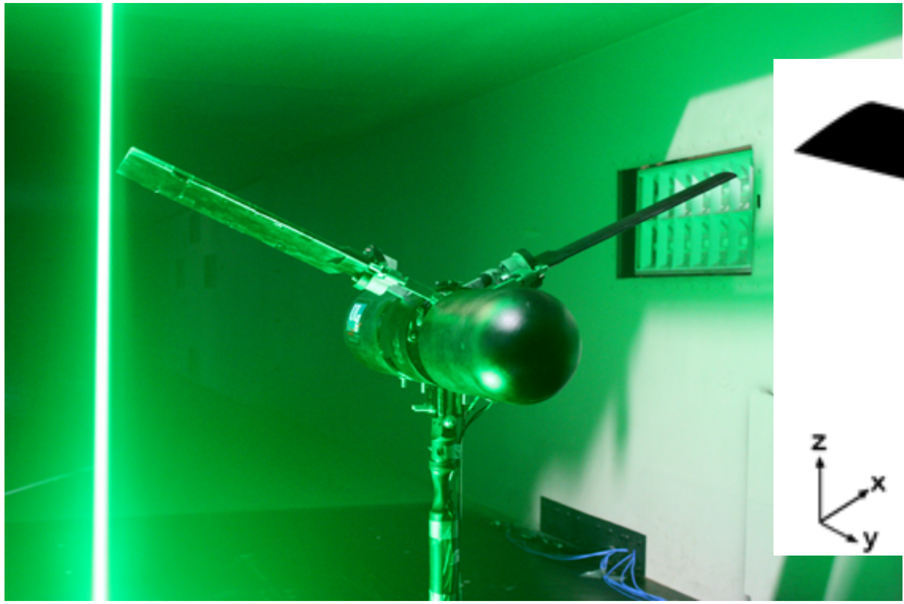
Inertial effect on force measurements

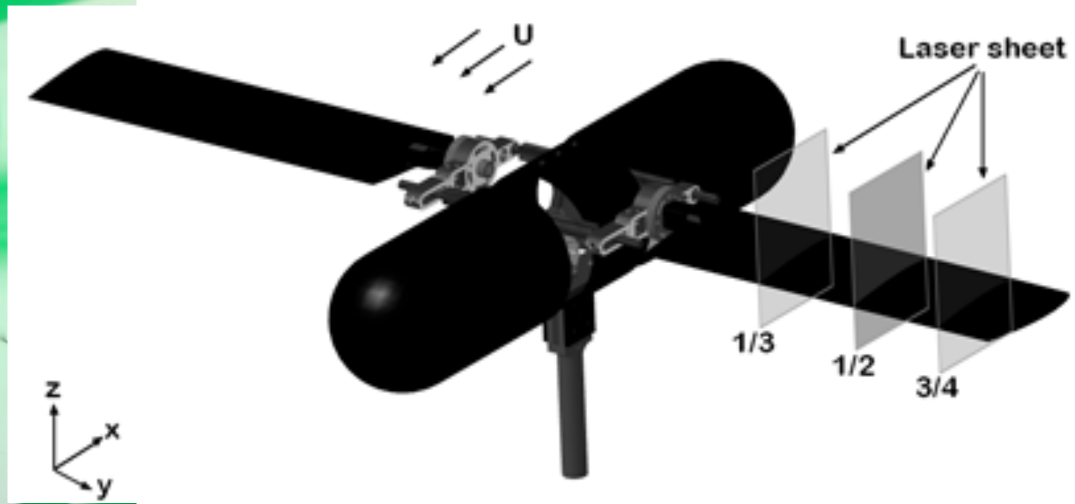
- The force sensors measure not only aerodynamic forces but also inertial forces due to the wing flapping.
- The two contributions must be separated in order to estimate the aerodynamic forces.



PIV flow visualization

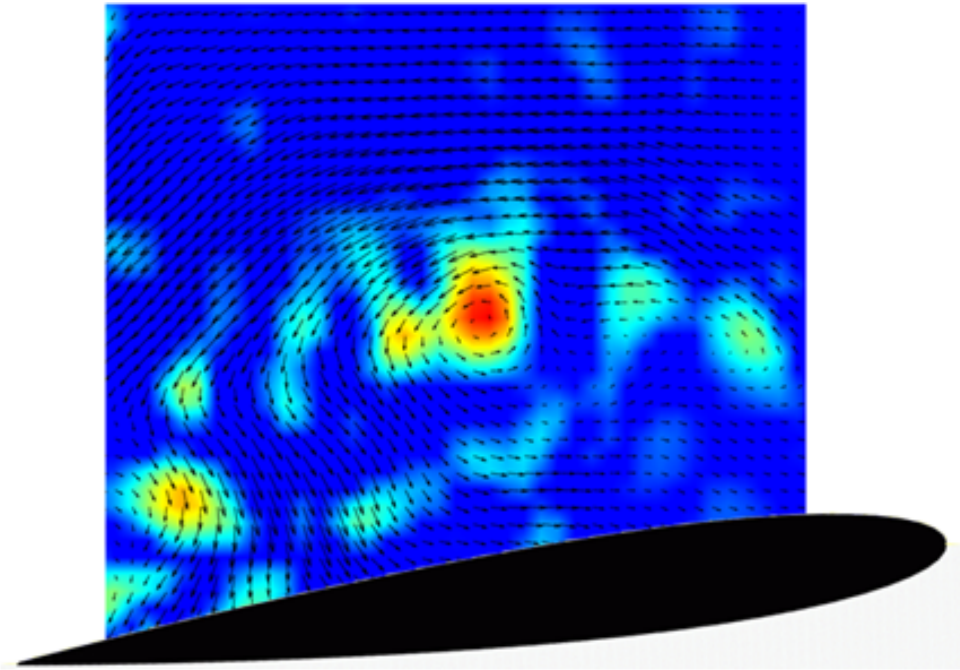
- Full sets of visualization were recently obtained
- We are in the process of analyzing the results.



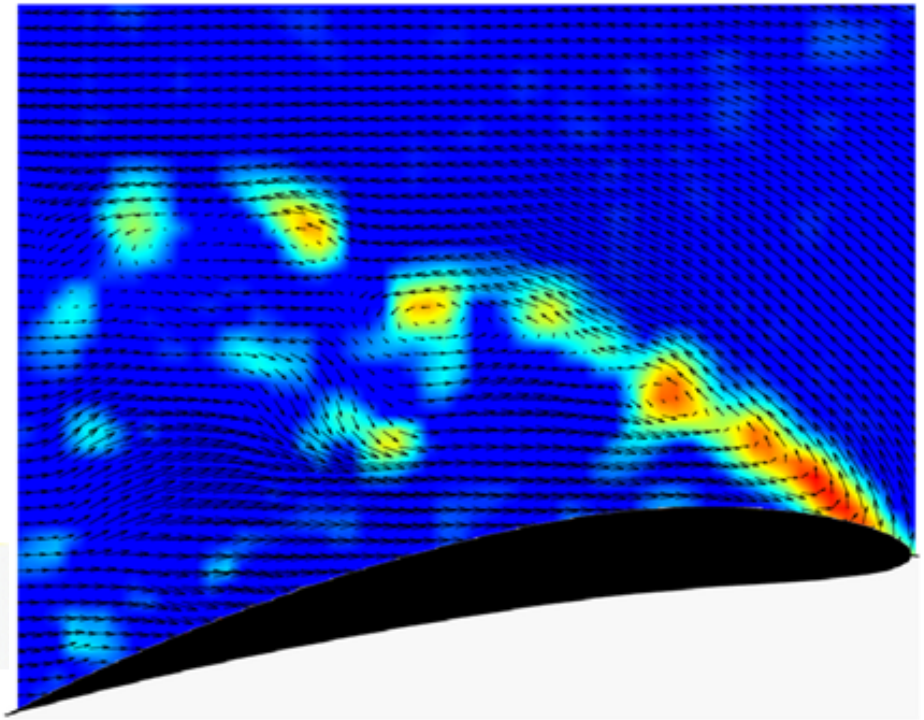


PIV examples

Separated flow areas during the downstroke for two of the tested wings



NACA 0012

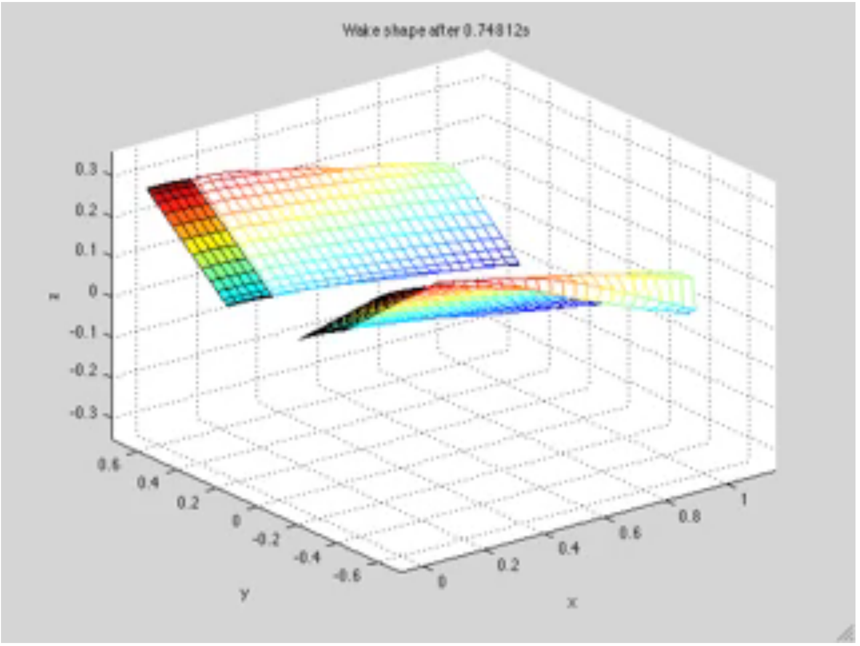


NACA 6409

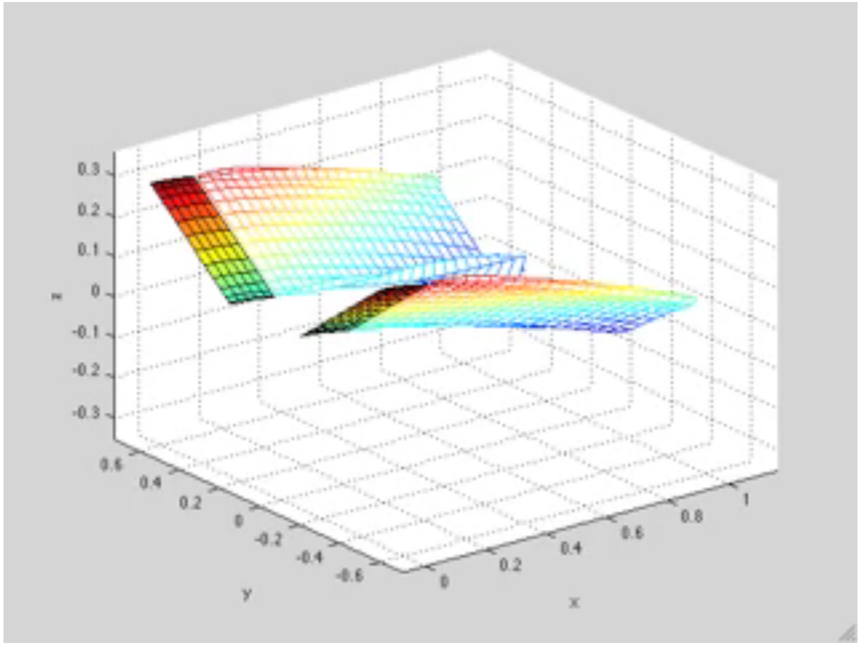
Vortex lattice simulation

- With vortex lattice, the wings are discretized into small panels on which lie vortex rings.
- The strength of the vortex rings is such that the flow cannot cross the wing's surface.
- The modeling is carried out at discrete time steps.
- At each time step a row of vortex rings is shed into the wake. The full wake is deformed at the local airspeed (free wake).
- Knowing the strengths of all the wing and wake vortex rings, we can calculate the aerodynamic forces.
- Of course, the wing flaps and pitches.

VLM simulation in action

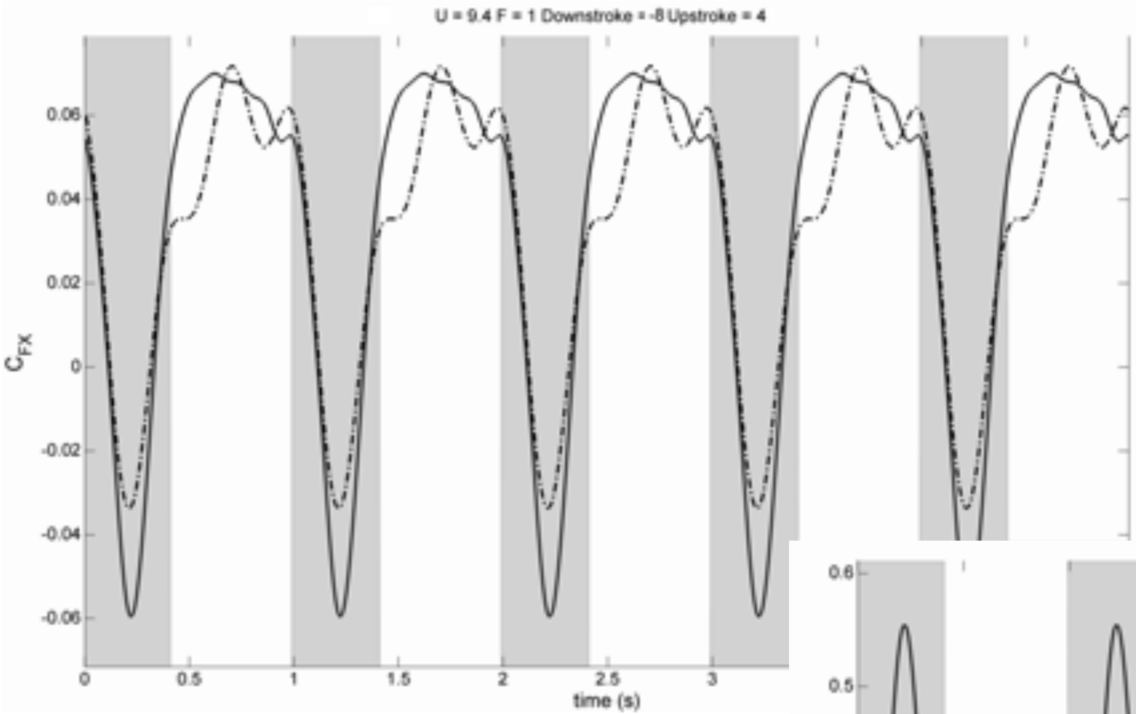


Mostly flapping



Flapping and pitching

Comparison: experiment vs simulation

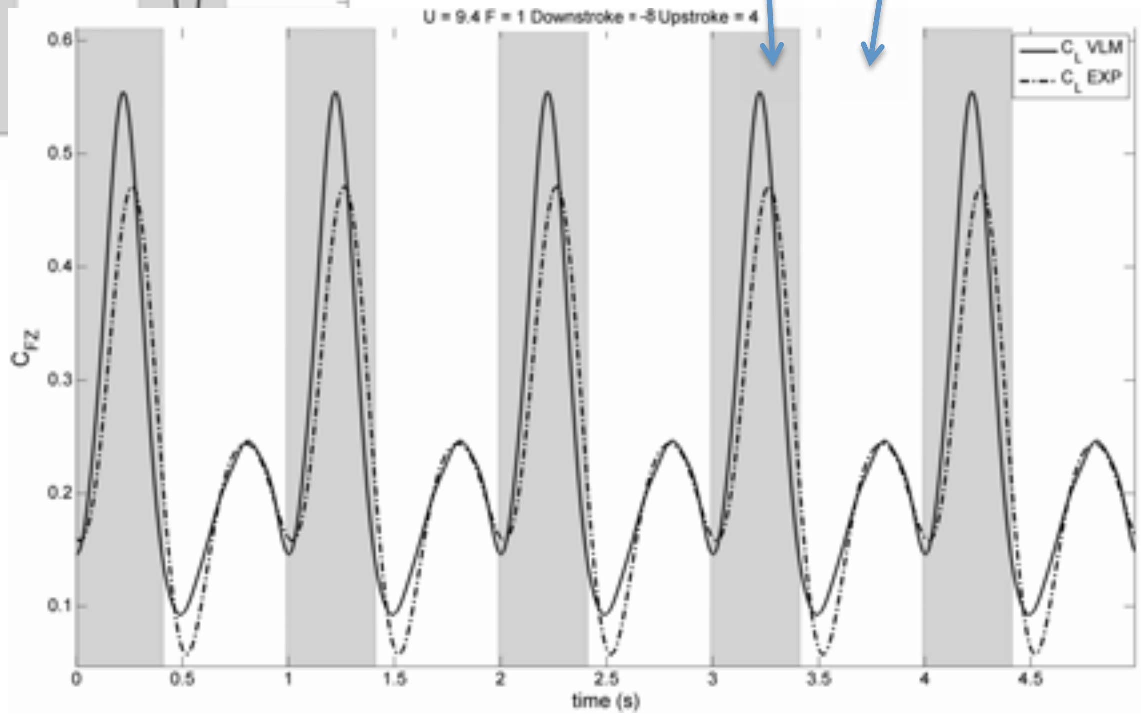


Drag

Downstroke

Upstroke

Lift



Very good comparisons were obtained between simulation and experiment. This example is for the NACA 6409 wing.

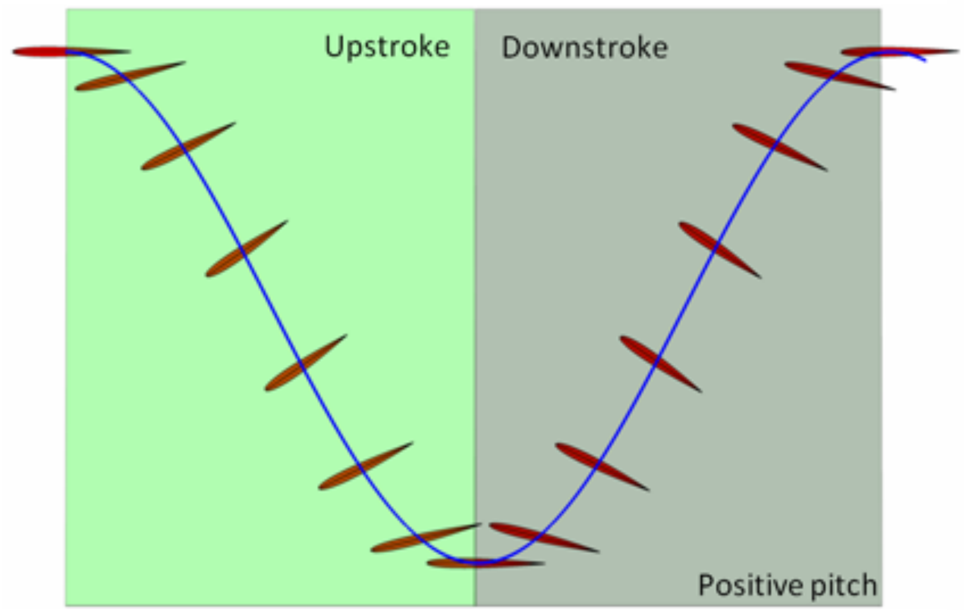
Thrust vs lift

- C_{FX} and C_{FZ} denote the total drag and lift coefficients for both wings in the wind axes.
- The previous results show that when maximum thrust is produced the lift is also maximum.
- On the other hand, drag is generated when the lift is low.
- This means that different parts of the cycle serve different purposes:
  - The downstroke produces a lot of lift and thrust
  - The upstroke generates mainly drag and little lift

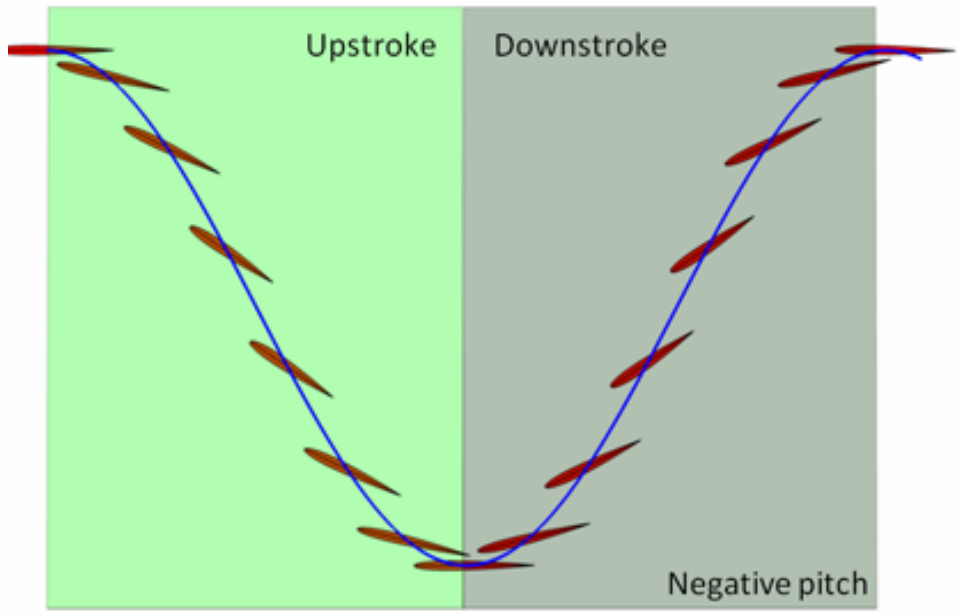
Thrust over a cycle

- So if both thrust and drag are produced over a cycle, how can we get a net thrust?
- The answer depends on the flapping mechanism. Let's deal with three different mechanisms:
  - Pure flapping
  - Pitch lagging
  - Pitch leading

Pitch lagging vs pitch leading



Pitch lagging

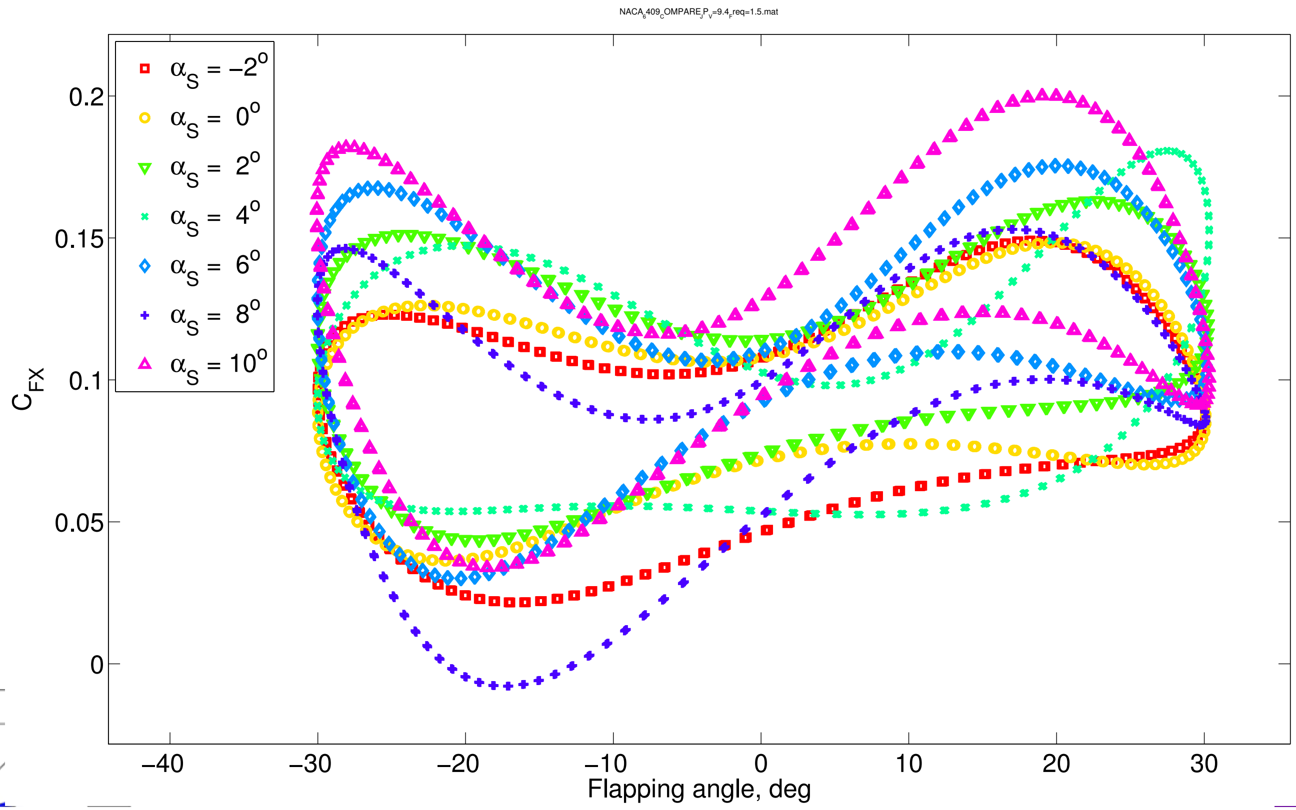


Pitch leading

- Pitch lagging: when the wind starts flapping down, the pitch starts increasing
- Pitch lagging: when the wind starts flapping down, the pitch also starts decreasing

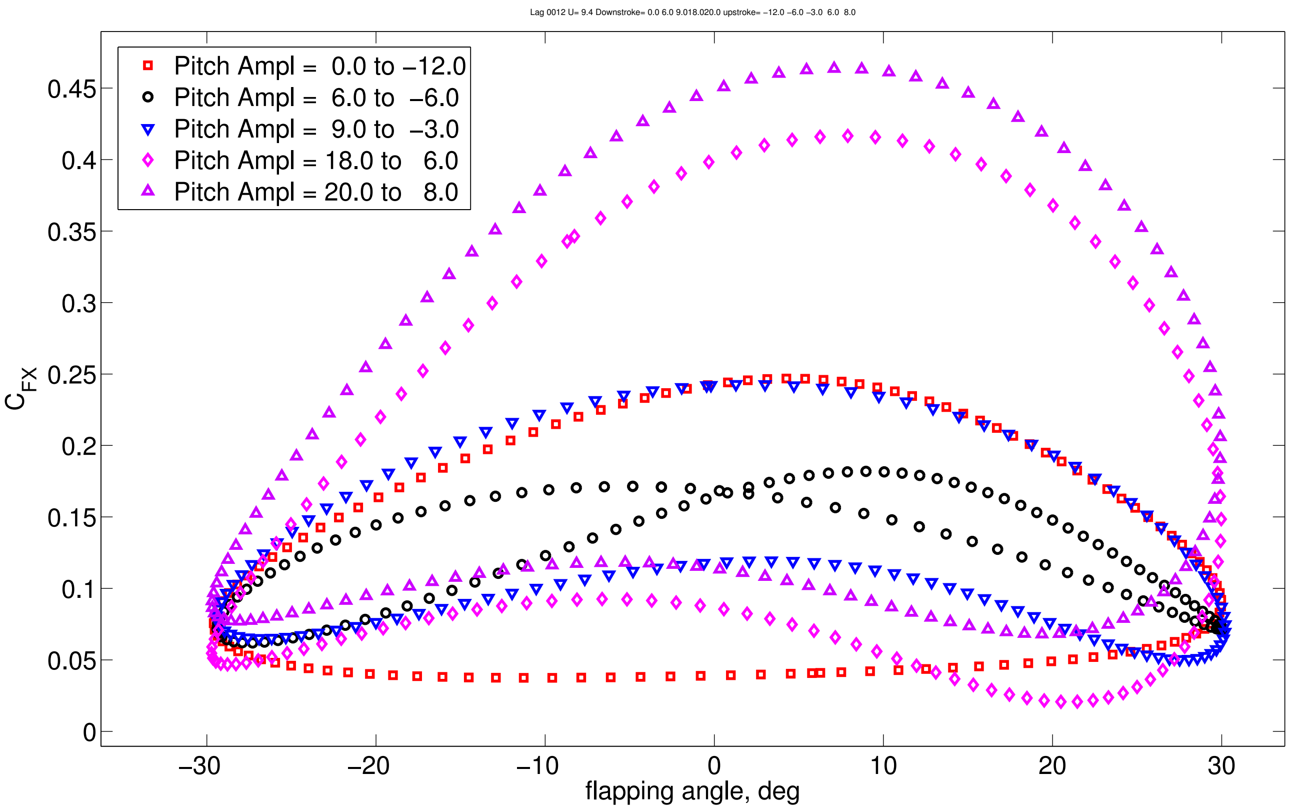
Pure flapping thrust

- Drag coefficient vs flapping angle for different constant pitch angles (NACA 6409)
- Drag is always produced, even for a small negative pitch angle.



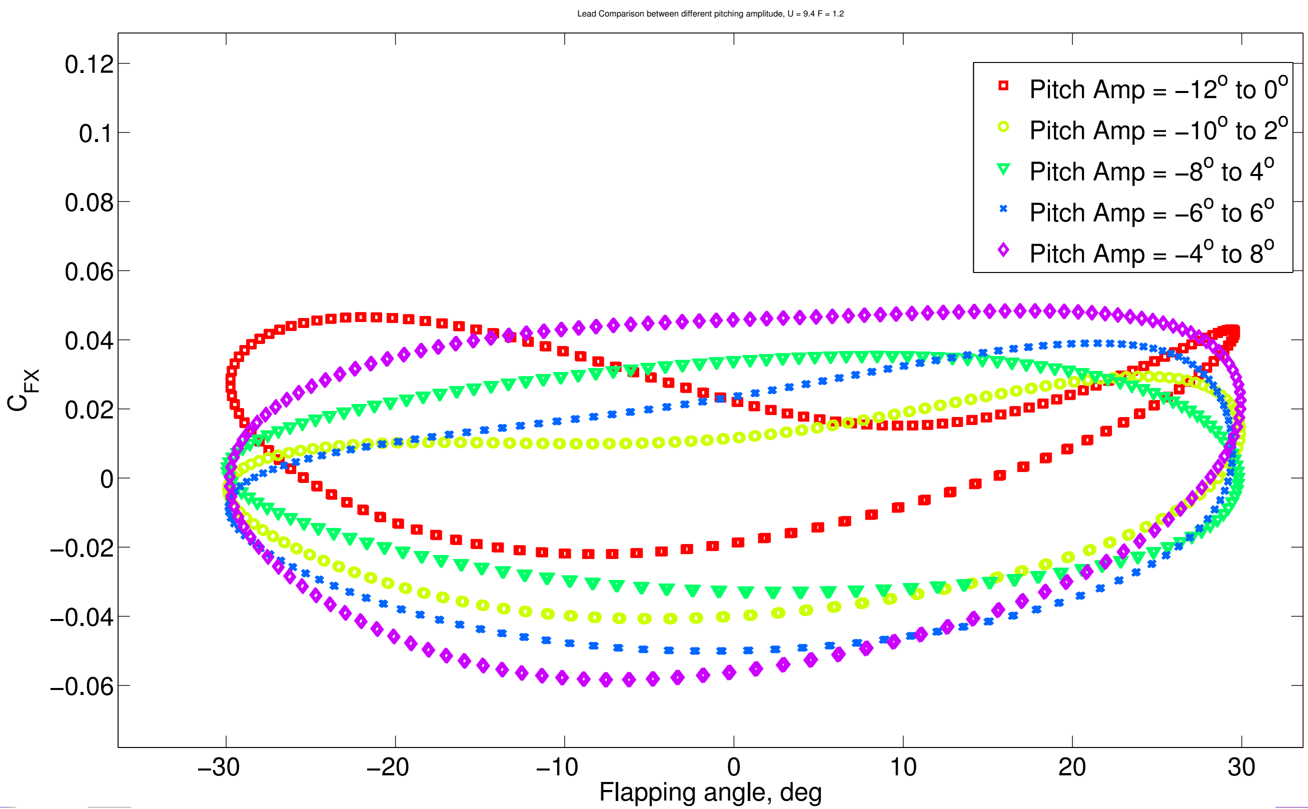
Pitch lagging

- Drag coefficient vs flapping angle for different pitch amplitudes (NACA 0012)
- Drag is always produced.



Pitch leading

- Drag coefficient vs flapping angle for different pitch amplitudes (NACA 0012)
- All configurations except the red one produce net thrust.

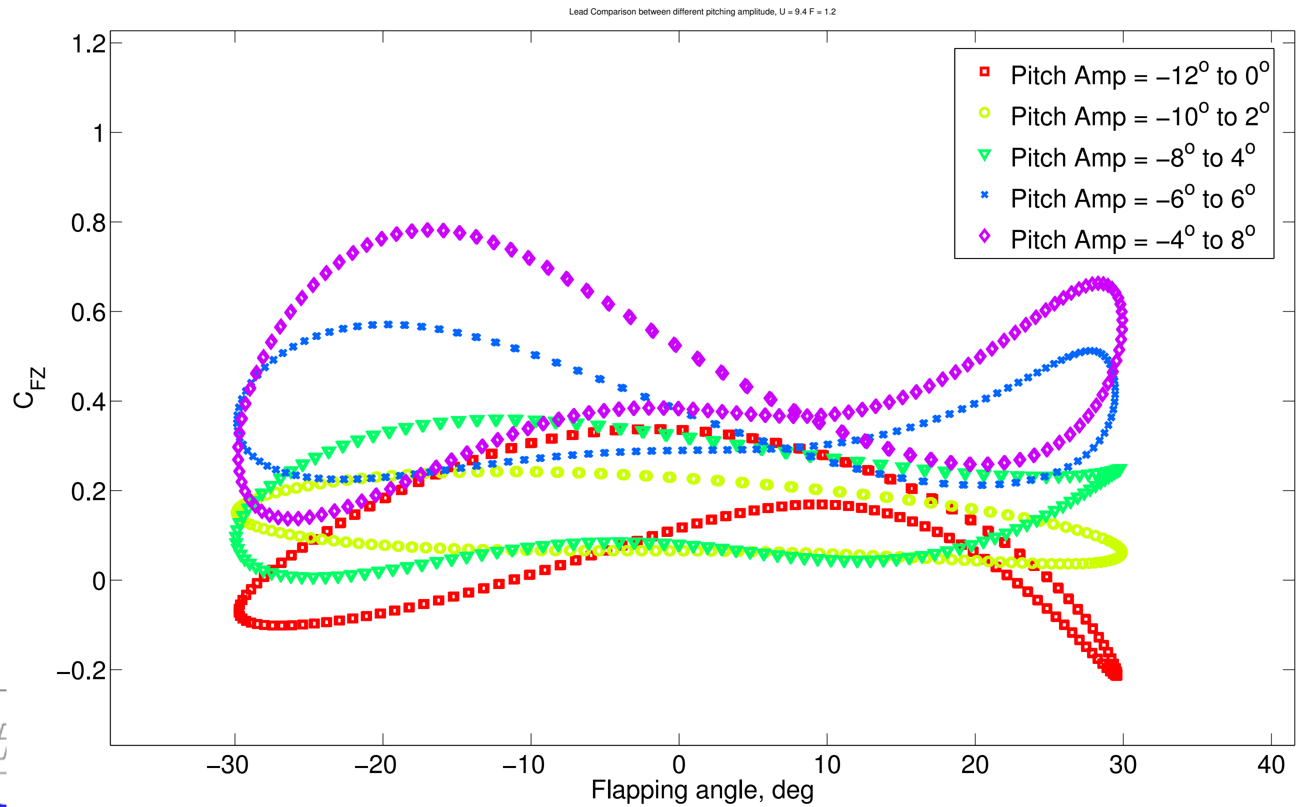


Thrust discussion

- Pure flapping in the 3D case, unlike the 3D case, cannot produce thrust.
- The only type of kinematics that will generate thrust is pitch leading. This means that the effective angle of attack of the wings must remain low at all times.
- Therefore, a necessary condition for thrust production is that the flow must remain attached on the wings' surface at all times.
- If the flow separates over part of the cycle, then net drag is produced.

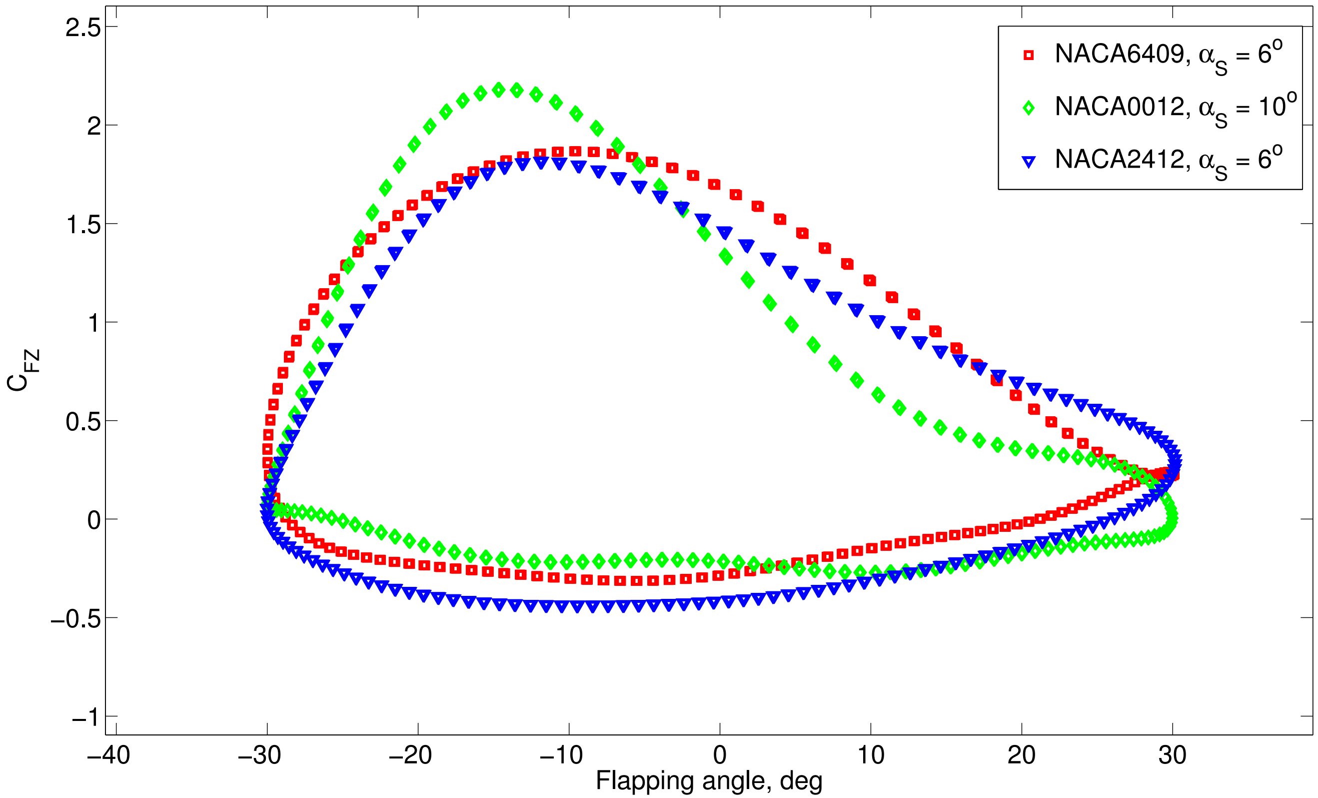
Lift production

- While attached flow can generate thrust, it does not generate very high amounts of lift.
- Lift coefficient variation against flapping angle, pitch leading case, NACA 6409. The maximum lift coefficient is around 0.8.



Dynamic stall

- Periodic flow separation is known as dynamic stall. It can generate much more lift than attached flow.
- Lift coefficient against flapping angle, pure flapping, all three wings. Maximum lift coefficient is over 2.



Conclusions

- Thrust can be generated when flapping and pitching but the pitch is leading, i.e. the effective angle of attack is small and the flow remains attached at all times.
- However, pitch leading results in low lift. Much higher lift can be obtained when the flow is allowed to separated (pitch lagging or pure flapping).
- Unfortunately, we can't get high lift and high thrust at the same time.
- Different kinematics must be used at different flight conditions:
  - Pitch leading for cruise
  - Dynamic stall for takeoff and rapid climb

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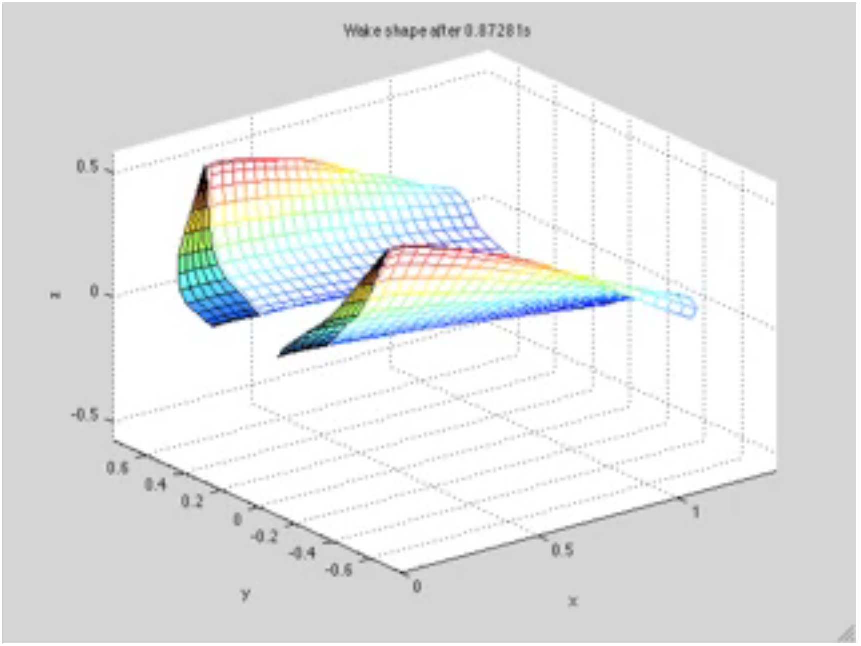
Future work (1)

- More bird-like wings and kinematics have already been implemented in the Vortex Lattice simulation.
  - Bird-like planforms
  - Wings can bend and twist during the cycle/



Future work (2)

- The flight of particular species of animals can thus be analyzed using the VLM method.
- Furthermore, the same species can be modeled experimentally using Frankenbird.
  - The characteristic wing shapes, planforms and kinematics can be used.
  - Bending and twisting cannot be implemented.
  - There is a flapping frequency limit, which depends on the weight of the wings.

Future work (3)

- In collaboration with the Faculty of Life Sciences of the University of Manchester we will study the flight of geese.
  - Movies of geese flying in the wind tunnel
  - Simulate these flights with VLM
  - Attempt to recreate these flights with Frankenbird.

Future work (4)

- We have also been awarded a grant from the Brussels-Wallonia Federation to study the flight of pterosaurs.
  - Carry out simulation work on planforms characteristics of pterosaurs.
  - Determine the kinematics that maximize lift and thrust production.
  - Build wings with planforms and shapes characteristic of pterosaurs.
  - Implement these wings on Frankenbird. Test using the simulated kinematics.
  - Determine whether these kinematics could be used by pterosaurs.

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