ITS Colloquium, The Institute for Theoretical Sciences,
University of Notre Dame, April 8, 2010

Reversed Flapping Flight & Inverted Hydrodynamical Drafting

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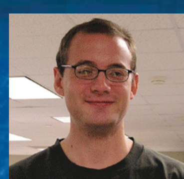

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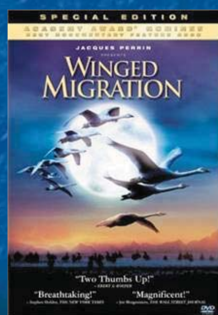
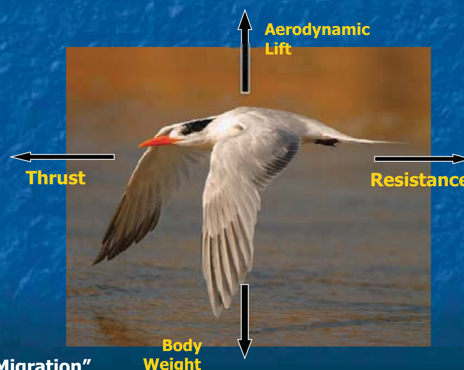
NSF-IGERT (DMS-9980069)

Flapping motion transverse to the direction of flight

No apparent pitching or rowing added to the flapping motion

Besides flapping, the wings appear to be somewhat rigid



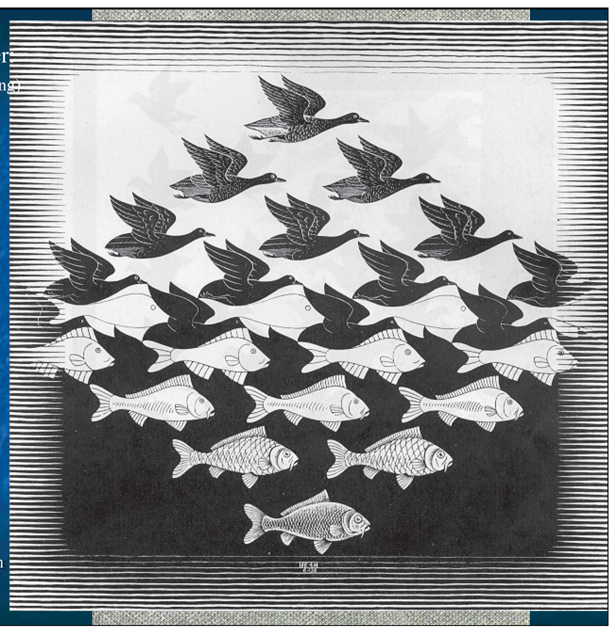


Please watch the movie "Winged Migration"

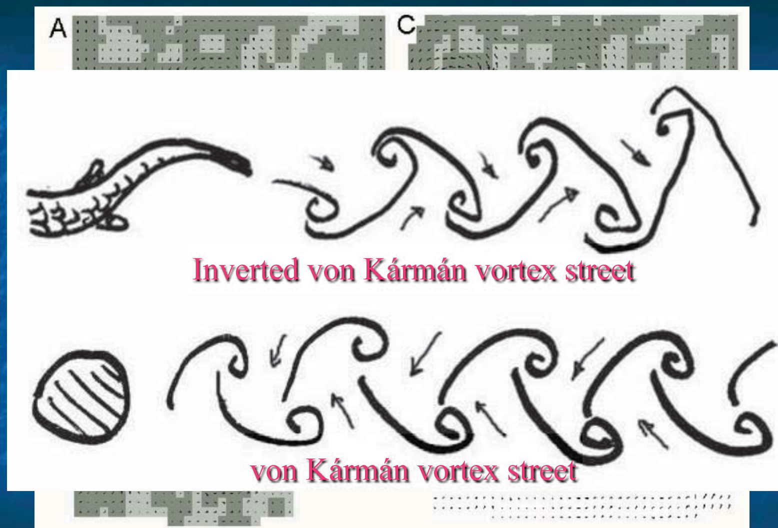
Taylor, Nudds, and Thomas, Nature **425**, 707, 2003; Fish and birds show same Strouhal number, close to 0.30.

The Reynolds number:
(inertia force/viscous damping)
Re = UL/ν

Fish and birds:
Re ~ $10^{3\text{-}5}$



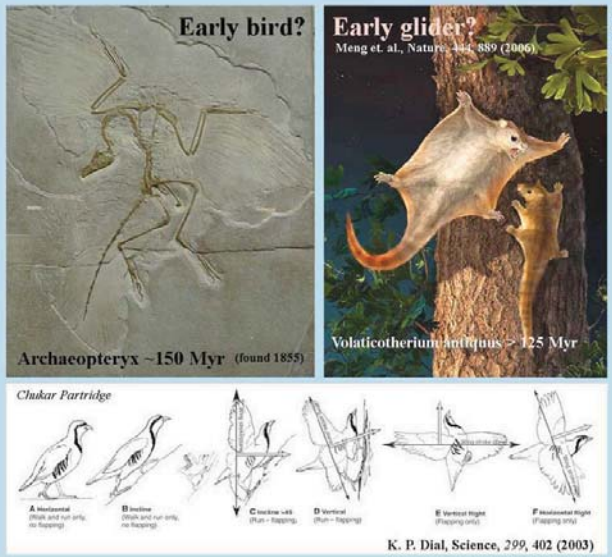
M. C. Escher (1898-1972)
Sky and Water, Woodcut
(I and II, 1938)
Fish and birds share similar mechanism to move about in water or in the air



Muller et. al., FISH FOOT PRINTS: MORPHOLOGY AND ENERGETICS OF THE WAKE BEHIND A CONTINUOUSLY SWIMMING MULLET, Journal of Experimental Biology **200**, 2893–2906 (1997)

What is the origin of flapping flight ?

The origin of flapping flight of large birds: from the ground up? Or from the trees down?



The debate on the origin of flight: from the ground up? from the trees down?

Q1: Can a simple, rigid, symmetric, flapping "wing" generate lateral **thrust**?

Q2: If the answer is "yes," what would be the thresholds (Reynolds number)?

(reciprocal motion leads to no net motion at low Reynolds numbers!)

Vandenberghe, Zhang and Childress, Journal of Fluid Mechanics, 2004
Alben and Shelley, PNAS, 2005
Vandenberghe, Childress and Zhang, Physics of Fluids, 2006
Rosellini and Zhang, 2009 (under review)

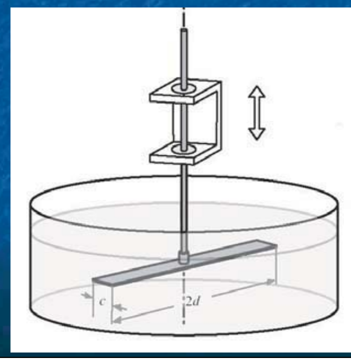
Flapping Mechanism and the Setup of Our Experiment

We work with a rotational geometry: a **symmetric**, **rigid** wing is flapped vertically but it is allowed to **freely rotate** (no rotation is imposed to the wing, any motion in the horizontal plane is entirely up to the wing-fluid interaction).

1. The "runway" is now "infinitely" long
2. Homogeneous friction at different positions along the "runway"
3. It's easier to measure speed, to visualize the flows

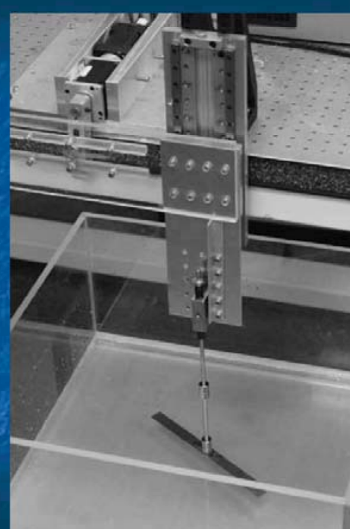
$$h(t) = \frac{a}{2}\sin(2\pi f t)$$

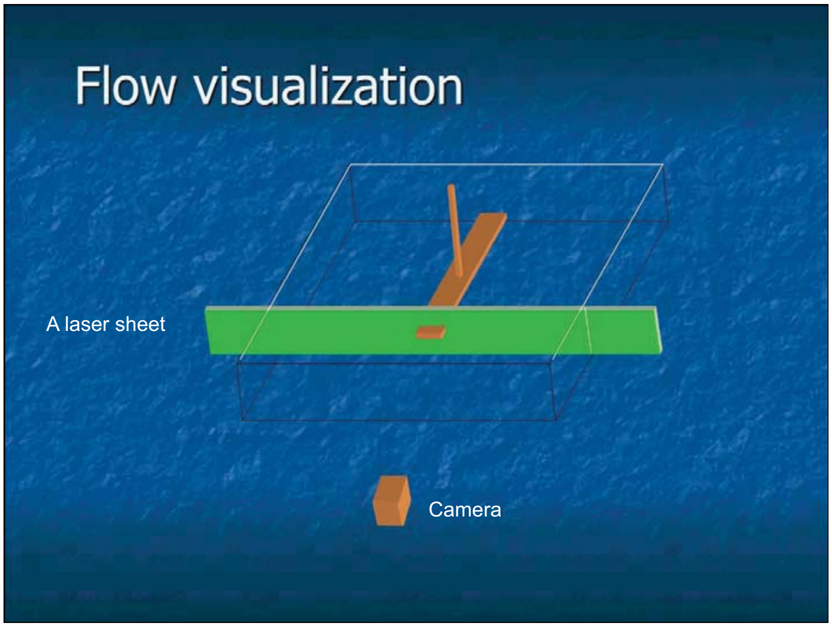
a: peak-to-peak flapping amplitude
f: flapping frequency
c: chord of the wing
$L=2d$: total length of the wing

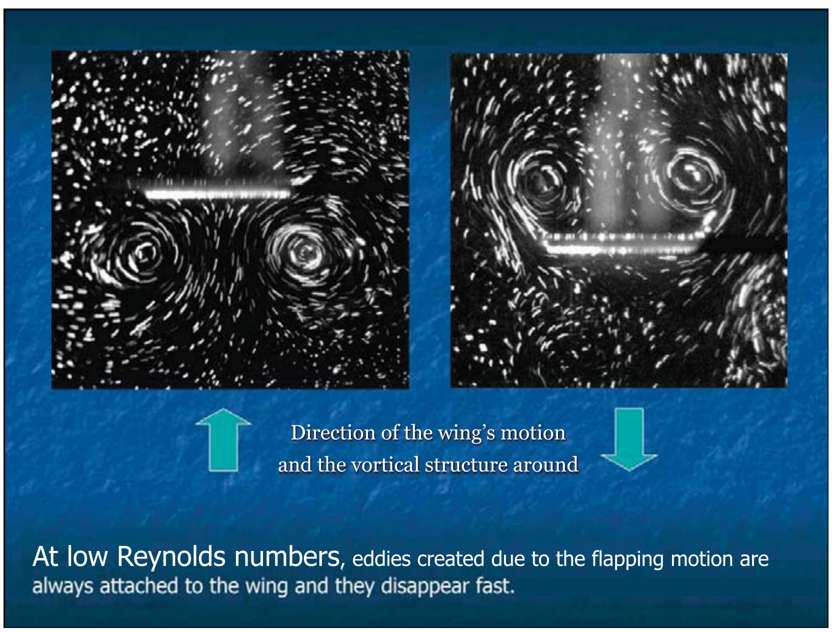


The experimental setups:

Generation I (2003) and generation II (2005).

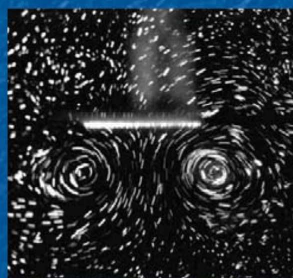


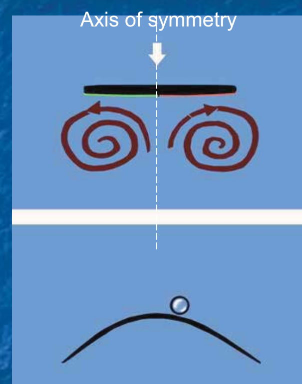

Flow visualization
A laser sheet
Camera


Direction of the wing's motion
and the vortical structure around
At low Reynolds numbers, eddies created due to the flapping motion are always attached to the wing and they disappear fast.

At higher Reynolds numbers: when eddies are still exist as the wing moves back….

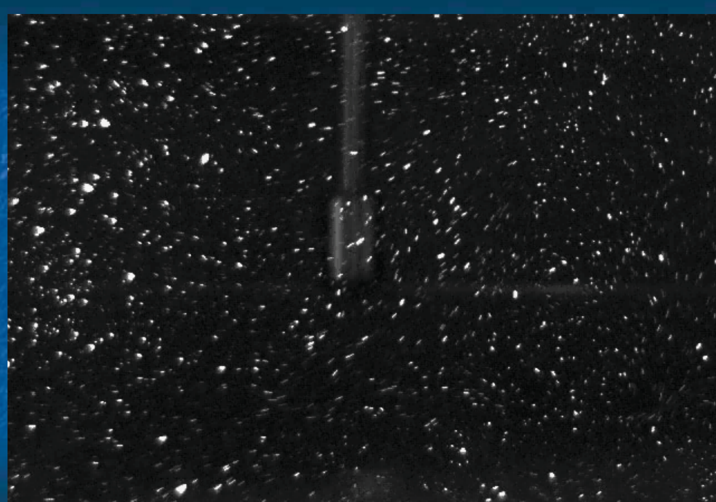
The primary instability: the system is at an unstable fixed point, easily breaks symmetry



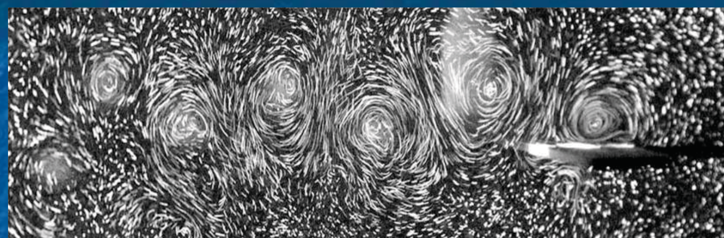


$F = +kx$

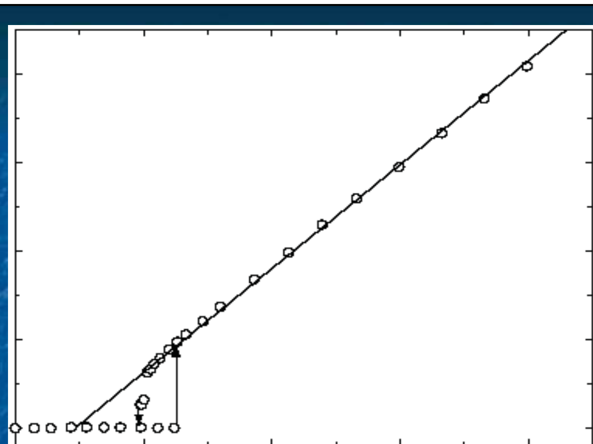
Spontaneous symmetry breaking bifurcation



Flow visualization of the wake after a flapping wing in "forward flight"



Forward Flight Speed [Re]



Flapping Frequency [in Reynolds number]

Vandenberghe, Zhang and Childress, Journal of Fluid Mechanics, 2004
Alben and Shelley, PNAS, 2005
Vandenberghe, Childress and Zhang, Physics of Fluids, 2006
Rosellini and Zhang, 2009 (under review)

The system (a flapping wing in an initially stationary fluid) losses stability to a forward, rotational motion: it performs a "**forward flight**".

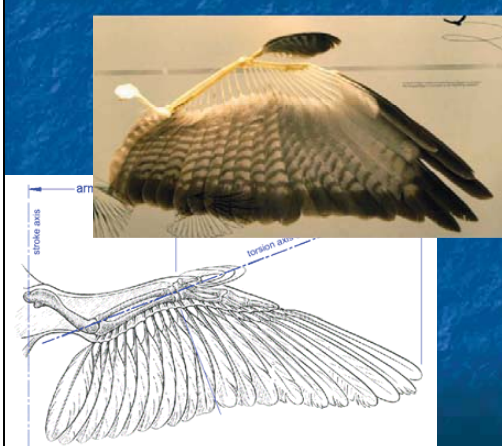
As a result of Spontaneous Symmetry Breaking:

The wing rotates (takes off) in either directions, with roughly the same probability. Once it "takes off" in one direction, it maintains that state.

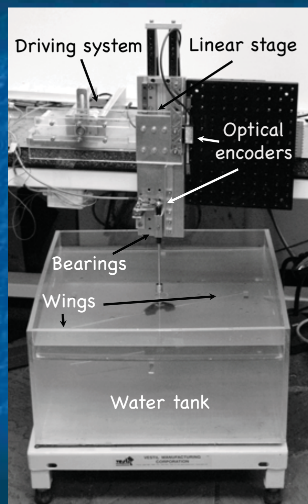
A "symmetric bird" would fly in unidirectional directions.

What is the effect of passive pitching in free flapping flight ?

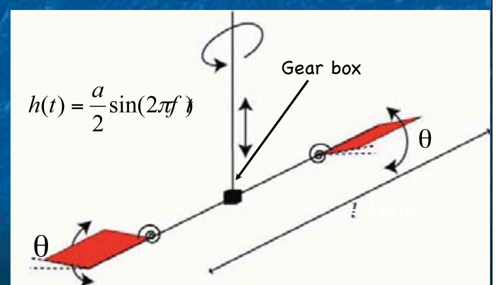
Most of the animals have *passive* flexing parts/appendages (wings and fins).
Is there any advantage to be (somewhat) flexible?

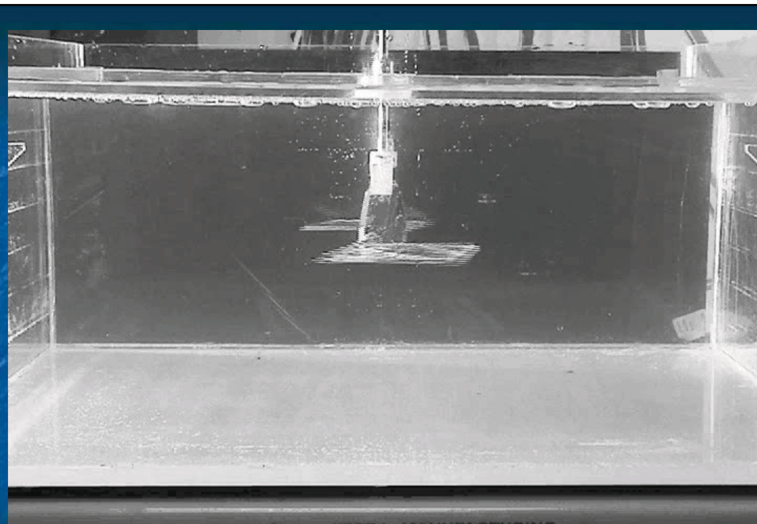


Experimental setup on passive pitching and free flight



- 0 < driving frequency f < 5 Hz
- 4 cm < chord C < 8 cm
- 1.6 cm < peak to peak amplitude a < 5.5 cm
- 0.04 Nm < torsional spring constant k < 0.15 Nm
- Gear box guarantees the equal pitching angle θ of the two wings.





Only the heaving motion in the vertical direction is prescribed, the pitching and the consequent unidirectional flight are passive responses of the fluid-structure interaction.

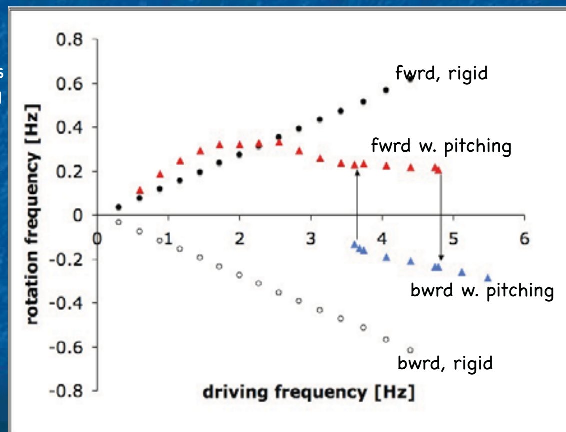
The main effects of passive pitching in free flight

$$Re = \frac{af\,c}{\nu} \sim 10^{4-5}$$

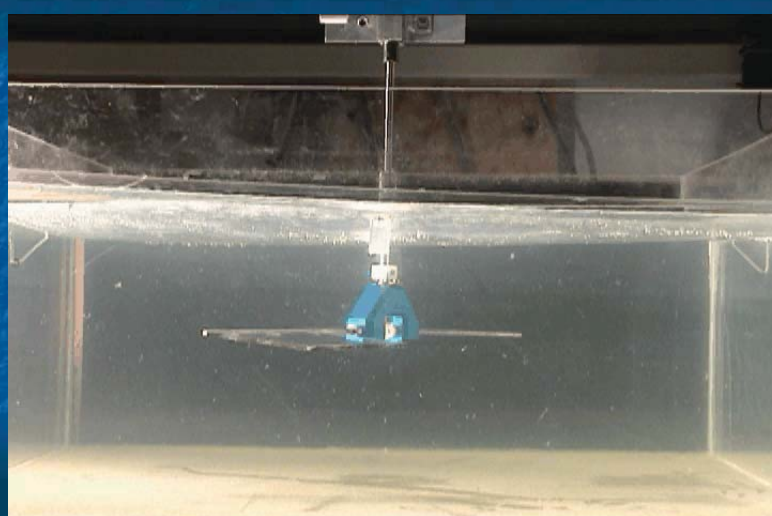
- Flapping amplitude: 2.7cm
- Wing chord: 8cm

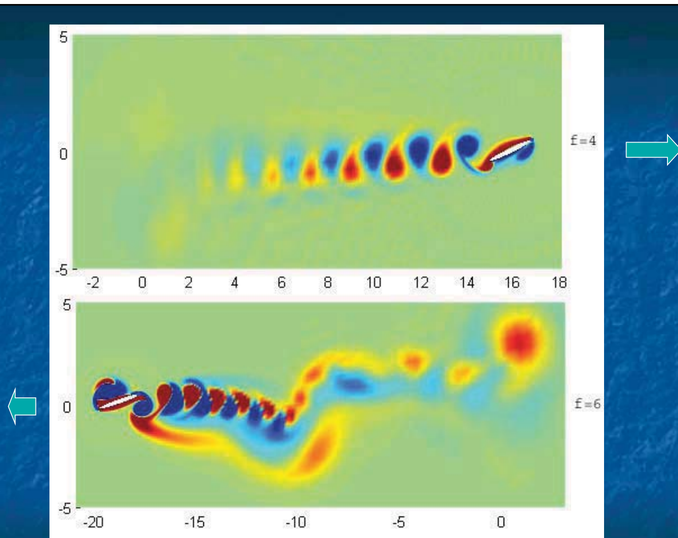
- Backward free flight is forbidden for low driving frequencies.
- Passive pitching can increase the speed for a given heaving motion.

- Flexibility introduces forward/backward transitions.
- Forward free flight is forbidden above a threshold.



The backward flapping flight:





S. Spagnolie et. al., Physics of Fluids, 2010

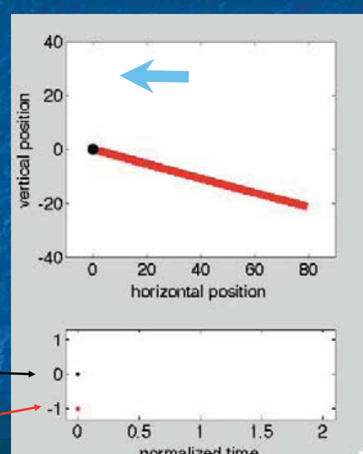
The anticipated motion of the wing

Heaving → Pitching

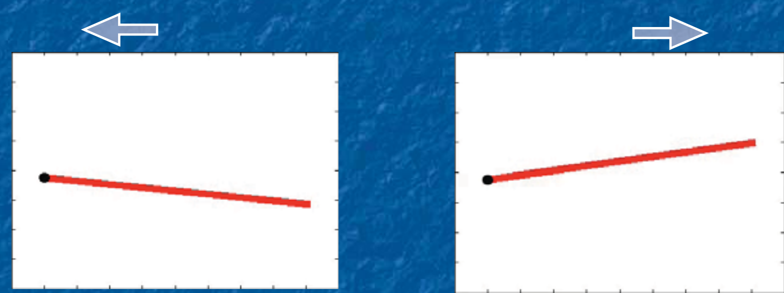
- A restoring torque constrains the angle of deflection.
- The phase between the heaving and the pitching depends on the heaving (frequency and/or amplitude).

Normalized vertical position of the leading edge.

Normalized angle of deflection.



The pitching behavior around the transition
from forward flight to backward flight



forward flight
rel. phase = 100°

backward flight
rel. phase = 194°

- Non-dimensional flexibility: *passive pitching*

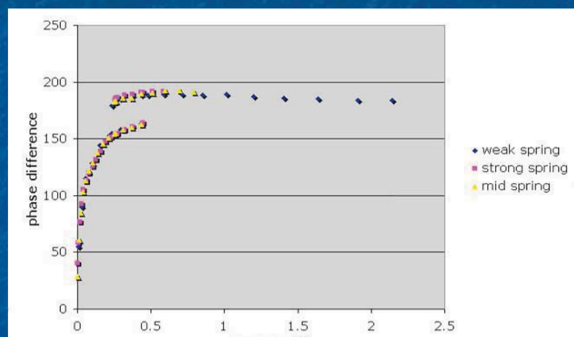
$$p = \frac{\text{hydrodynamical pitching torque}}{\text{torsional spring constant}}$$

$$= \frac{[(\frac{1}{2}C_D \rho U^2)A](\frac{1}{2}c)}{\kappa} = \frac{\frac{1}{4}C_D \rho lc(\pi af)^2 c}{\kappa}$$

Is this dimensionless number P a good control parameter?

If yes, we should be able to see "*data-collapse*" using P to represent different systems with varying spring constant.

With different spring constant k = 0.04 Nm, 0.11 Nm and 0.16Nm.



Passive Pitching P

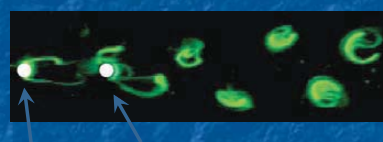
S. Spagnolie, L. Moret, M. Shelley and J. Zhang, Physics of Fluids, 2010

On swimming of "passive" fish
("swimming" of dead fish or flapping flags)

and

on "schooling" of many swimmers

Drafting of rigid bodies -- drag reduction for followers

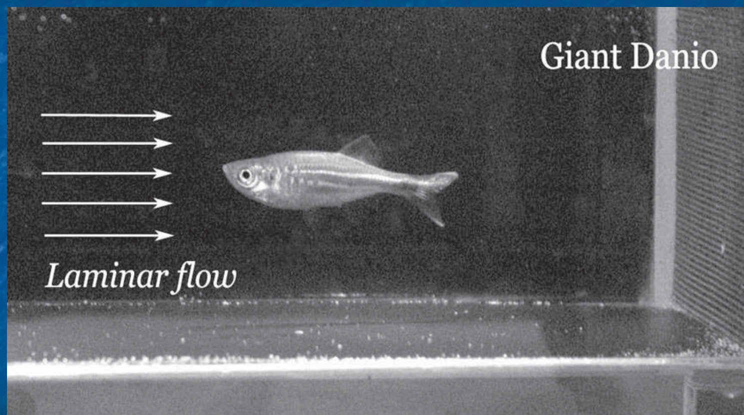


Bicyclists: Kyle, C. R. *Ergonomics* **22**, 387-397 (1979).
Racecars: Romberg, C. F., Chianese, Jr., F., & Lajoie, R. G. *Soc. Auto Eng.* 710213 (1971).
Cylinders: Zdravkovich, M. M. *J. Fluids Eng.* **99**, 618-633 (1977).

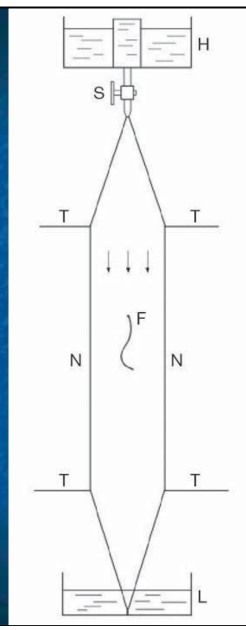
What happens when deformable bodies interact?

Schools and flocks: Fish, F. E. *Comments Theor. Biol.* **5**, 283-304 (1999).
Leaves in a breeze: Vogel, S. *Life in Moving Fluids* (Princeton Univ. Press, Princeton, 1994).
Waves of grain: Inoue, E. *J. Agric. Met.* (Japan) **11**, 71 (1955).

Swimming in a water current



Fish rheotaxis: game fish in water tunnel, New York Univ.



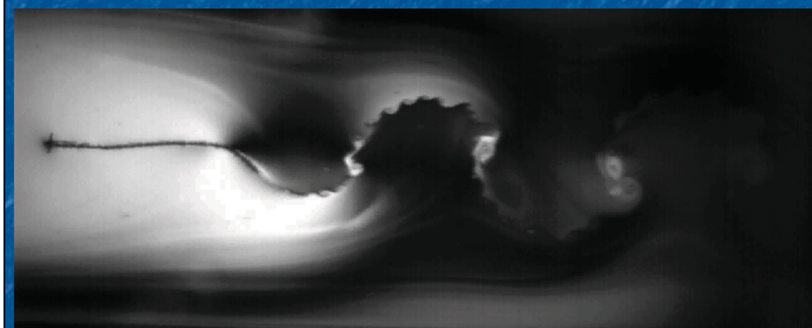
A single, lone flag first (a passive swimmer)!

A quasi-two-dimensional flowing soap film provides a laminar “wind or water tunnel.”

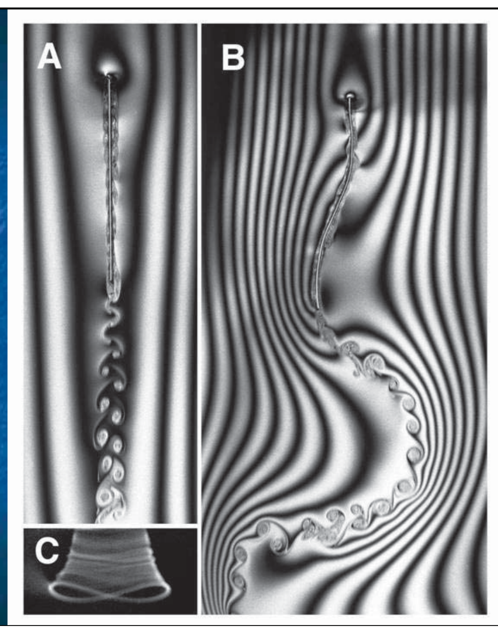
The 1D flap is a thin silk or rubber thread

The magic portion

A single, isolated flag in its flapping state:
Soap film flow direction (at up to 3m/sec)

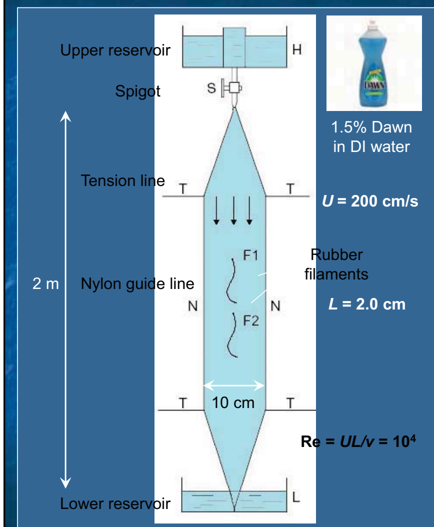


Flapping frequency f = 25 to 60 Hz, depends on the flow speed…



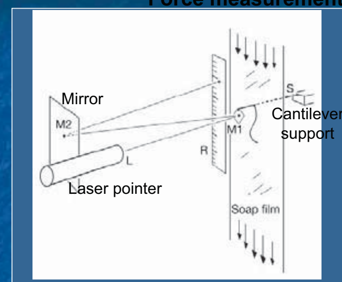
1D flag in a 2D wind,
Nature **408**, 835 (2000)

Flag pair and force (drag) measurement:

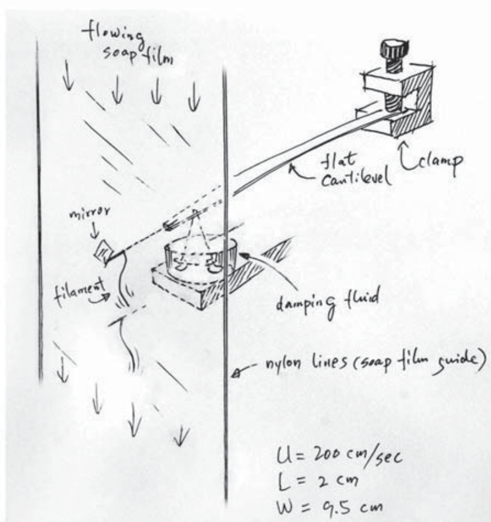


1.5% Dawn in DI water

Force measurement



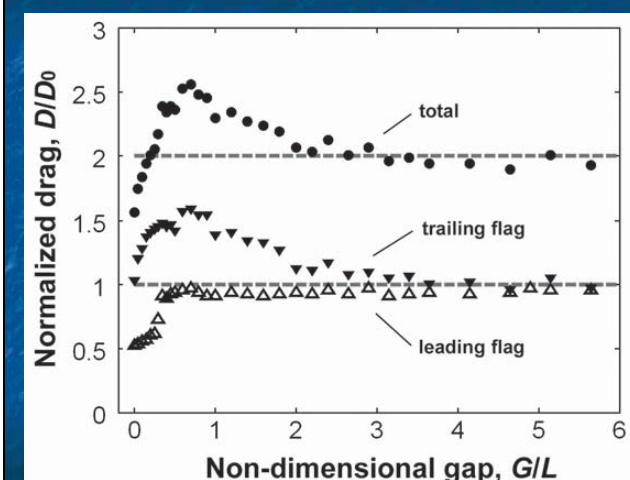
Soap tunnel:
Kellay, H., et. al. *Phys. Rev. Lett.* **74**, 3975 (1995)
Rutgers et. al., Rev. Sci. Inst., **72** 3025 (2001)
Force measurement:
Alben, S., Shelley, M., and Zhang, J.
Nature **420**, 479 (2002)
Flags:
Zhang, J., et. al. *Nature* **408**, 835-839 (2000)
Shelley, M, Vandenberghe, N. and Zhang J.
Phys. Rev. Lett. **94**, 094302 (1995)



Details on the force measurement: a Voigt element that measures a time-averaged force

"Anomalous hydrodynamic drafting of interacting flapping flags" Ristroph and Zhang, Phys. Rev. Lett., **101**, 184502 (2008)

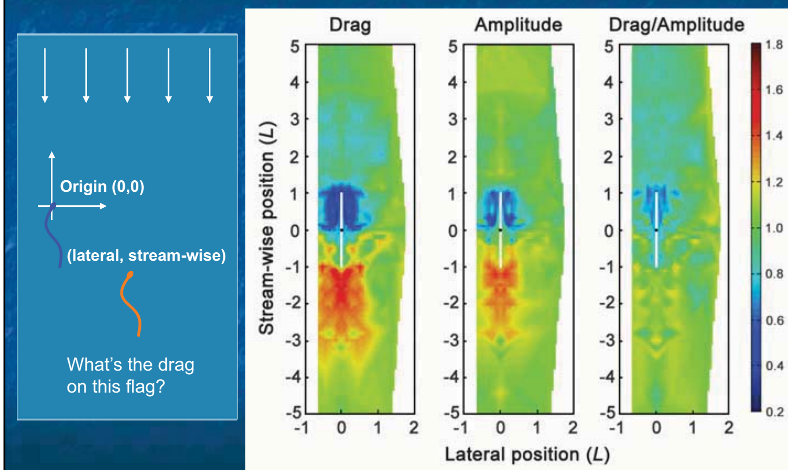
Inverted drafting -- To reduce drag, flap in front!



Drag on two independent flags

Drag on a single, isolated flag

Drag and flapping amplitude dependence on 2D displacement



Drag ~ Amplitude of flapping

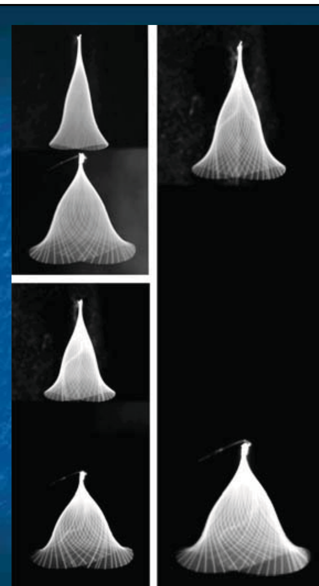
$$\text{Drag} = \frac{1}{2} C_D \rho U^2 S$$

Drag coefficient Fluid density Flow speed Area

Film thickness Amplitude

$$S \propto d \cdot A$$

Drag ~ Amplitude ($D \sim A$)

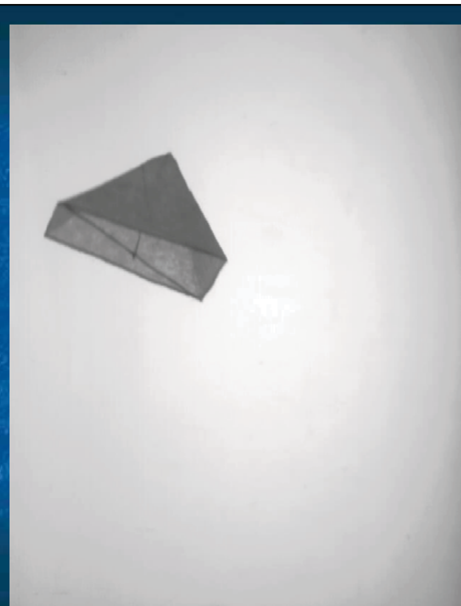


Try to explain this inverted drafting

Down-stream neighbor "pins" lateral flow → small amplitude for leader

Up-stream neighbor creates an oscillating wake → follower resonates with high amplitude

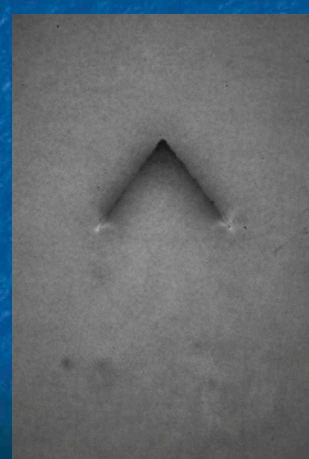
One of the first real-time movies from the experiment:



Flow visualization using a rigid plastic bug, sloshing water currents and shadowgraphs.

See how a downwash is produced as two pairs of vortices emerge within each cycle.

Stability !



Some conclusions:

Part I. With passive pitching, a flapping wing may reverse its flight direction. There is a dimensionless number that demarcates the transition. Competition between two time scales…

Part II. With rigid bodies, there is a tendency to form aggregates, due to the fact the follower experiences less drag than leader. (cyclists do form clusters…)

With flexible bodies, as seen here, an aggregate is not stable: the follower has more drag than the leader. Does this stabilize a fish school?

How about actively flapping bodies (our initial motivation, such as birds and fish). **It is still an open question.**

We have work to do...

Some related papers (as PDF files) can be found at: http://physics.nyu.edu/jz11/

"Surprising behavior of a flapping wing with passive pitching," Physics of Fluids, **22**, 041903 (2010)

"Anomalous hydrodynamic drafting on interacting flapping flags," Physical Review Letters, **101**, 194502 (2008)

"The effect of geometry of simple flapping wing," Under review with Phys. Rev. Lett., (2009)

"On unidirectional flight of a free flapping wing," Physics of Fluids, **18**, 014102 (2006)

"Heavy flags undergo spontaneous oscillations in flowing water," Physical Review Letters, **94,** 094302 (2005)

"Symmetry breaking leads to forward flapping flight," Journal of Fluid Mechanics, **506**, 147 (2004)

"Flexible filaments in a flowing soap film as a model for one-dimensional flags in a two-dimensional wind," Nature, **408**, 835 (2000)

Thank you!

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