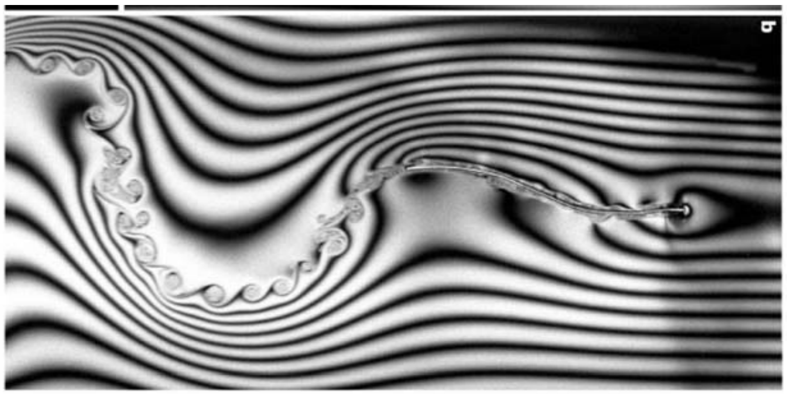
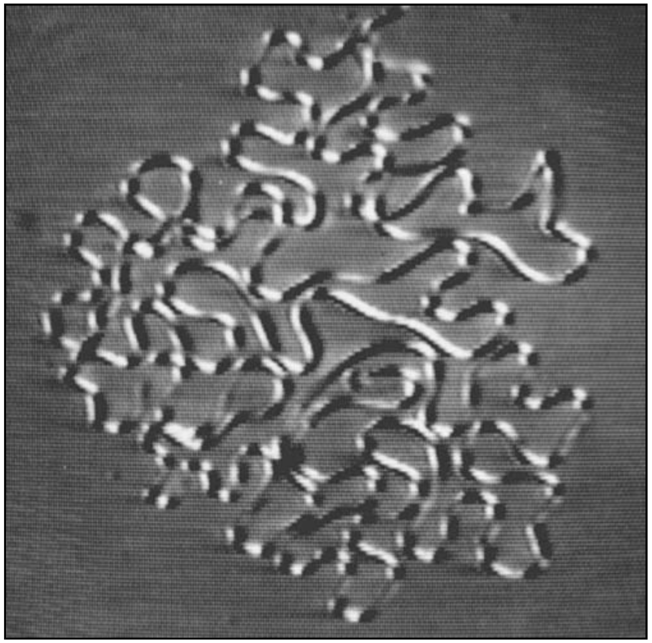
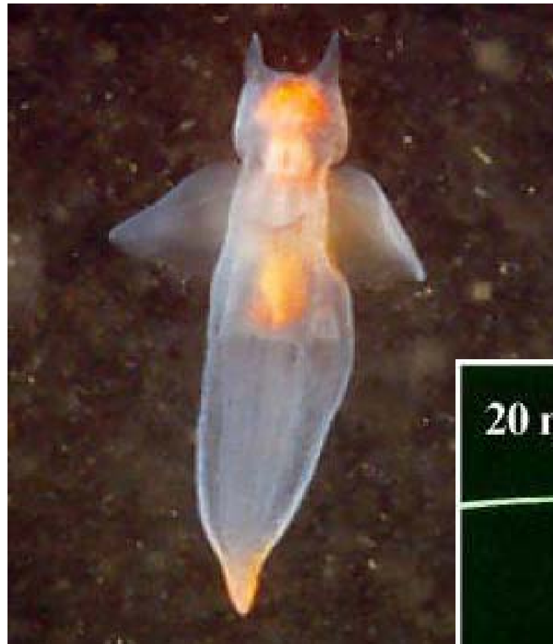
Flapping dead fish and flight

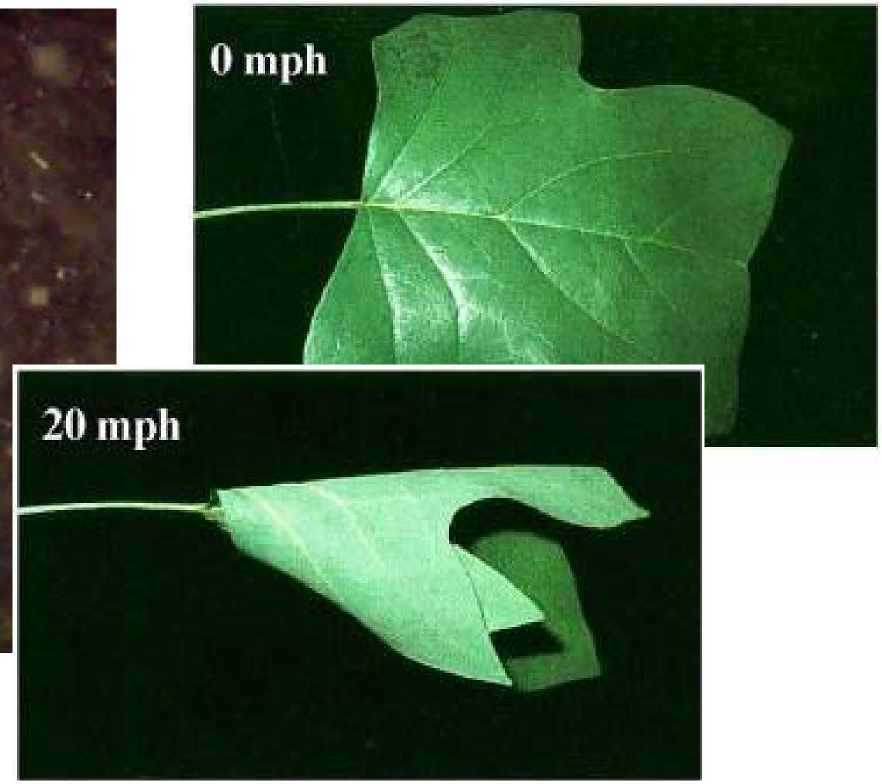


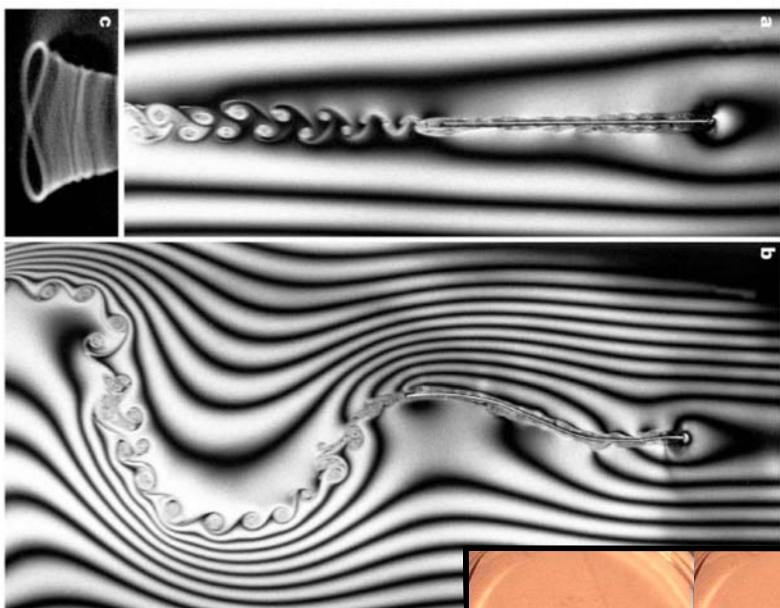
Main collaborators: Jun Zhang, Silas Alben, Saverio Spagnolie

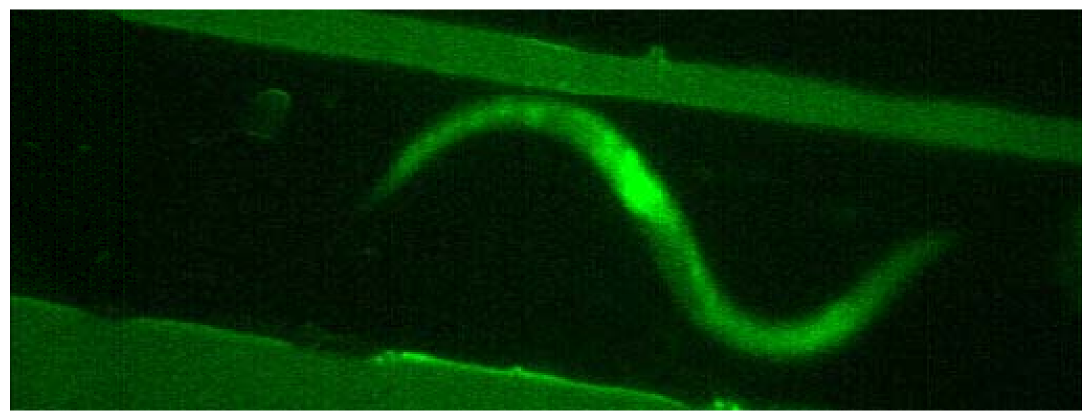
Some moving/deforming bodies interacting with fluids

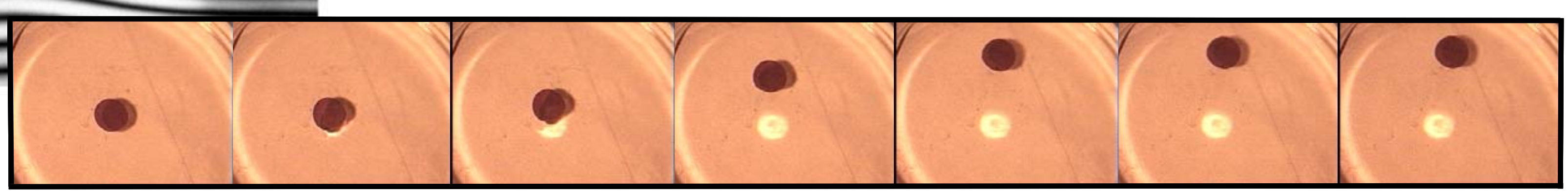




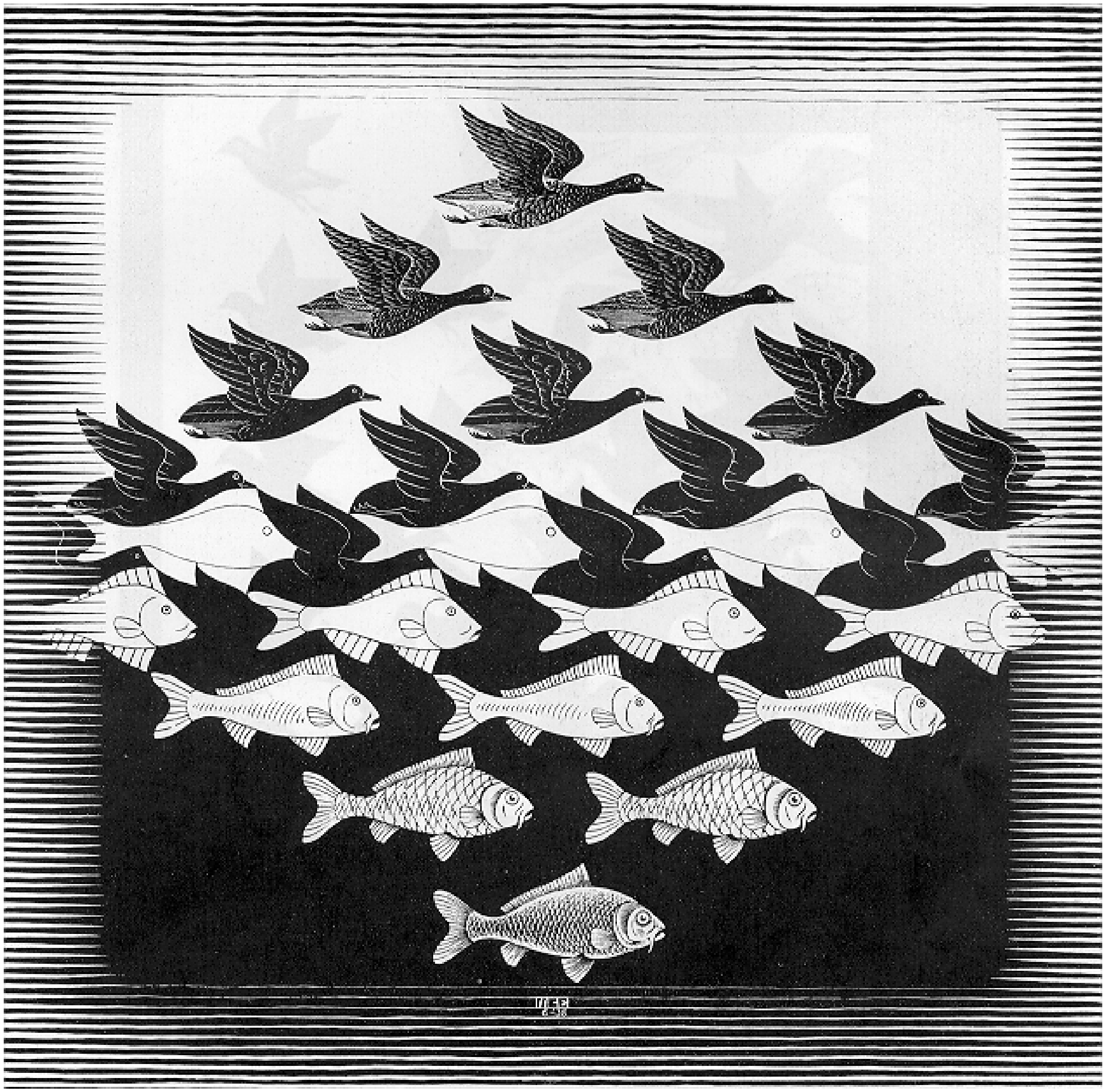








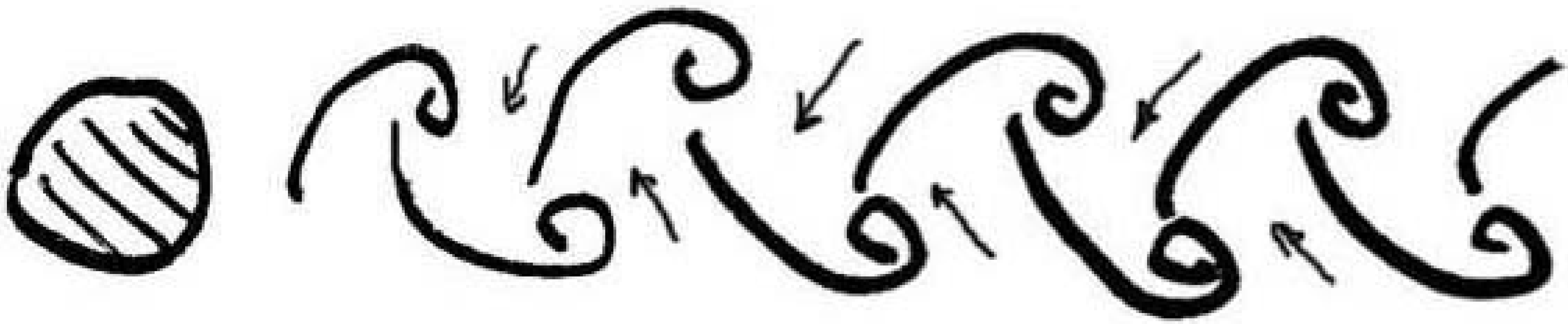
t = 0 5.0 5.5 6.0 6.5 7.0 9.0 s



Fish and birds share similar mechanisms to move about in water or in air.

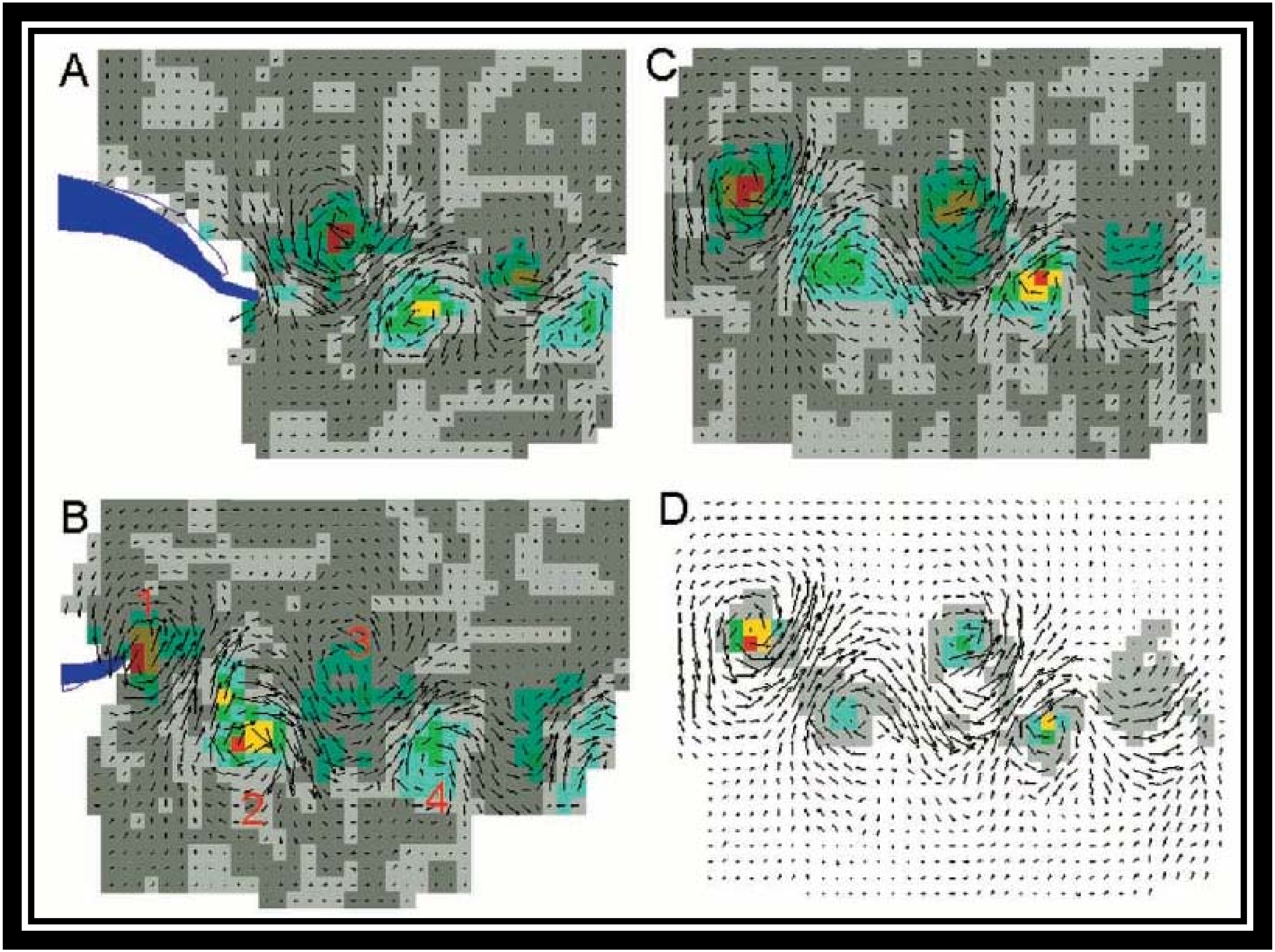
$$Re \sim 10^{3-5}$$

Drag wakes vs. Thrust wakes



von Kármán vortex street

Inverted von Kármán vortex street



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)

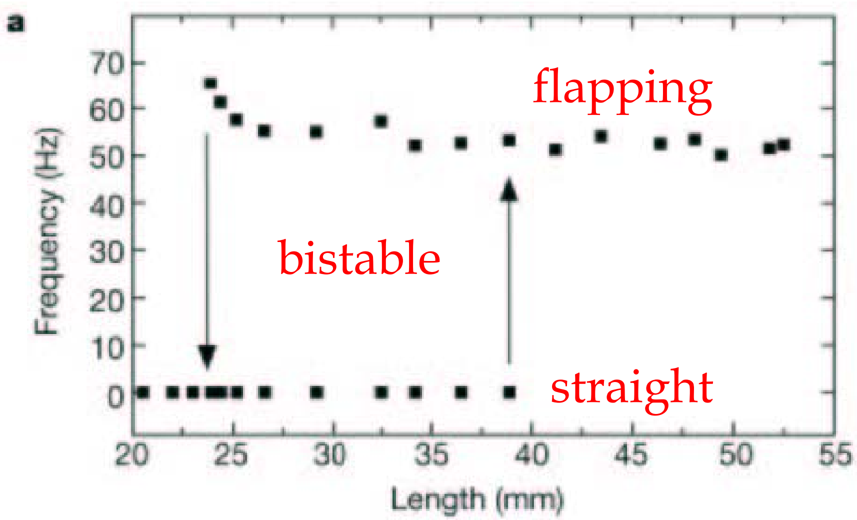
An early debate about fluid-structure interactions ...

Hui-Neng (638-713)

Flags flapping in soap films: A 1-d flag flapping in a 2-d wind

Zhang, Childress, Libchaber, Shelley, *Nature* 2000
Shelley, Vandenberghe, Zhang, *PRL* 2005

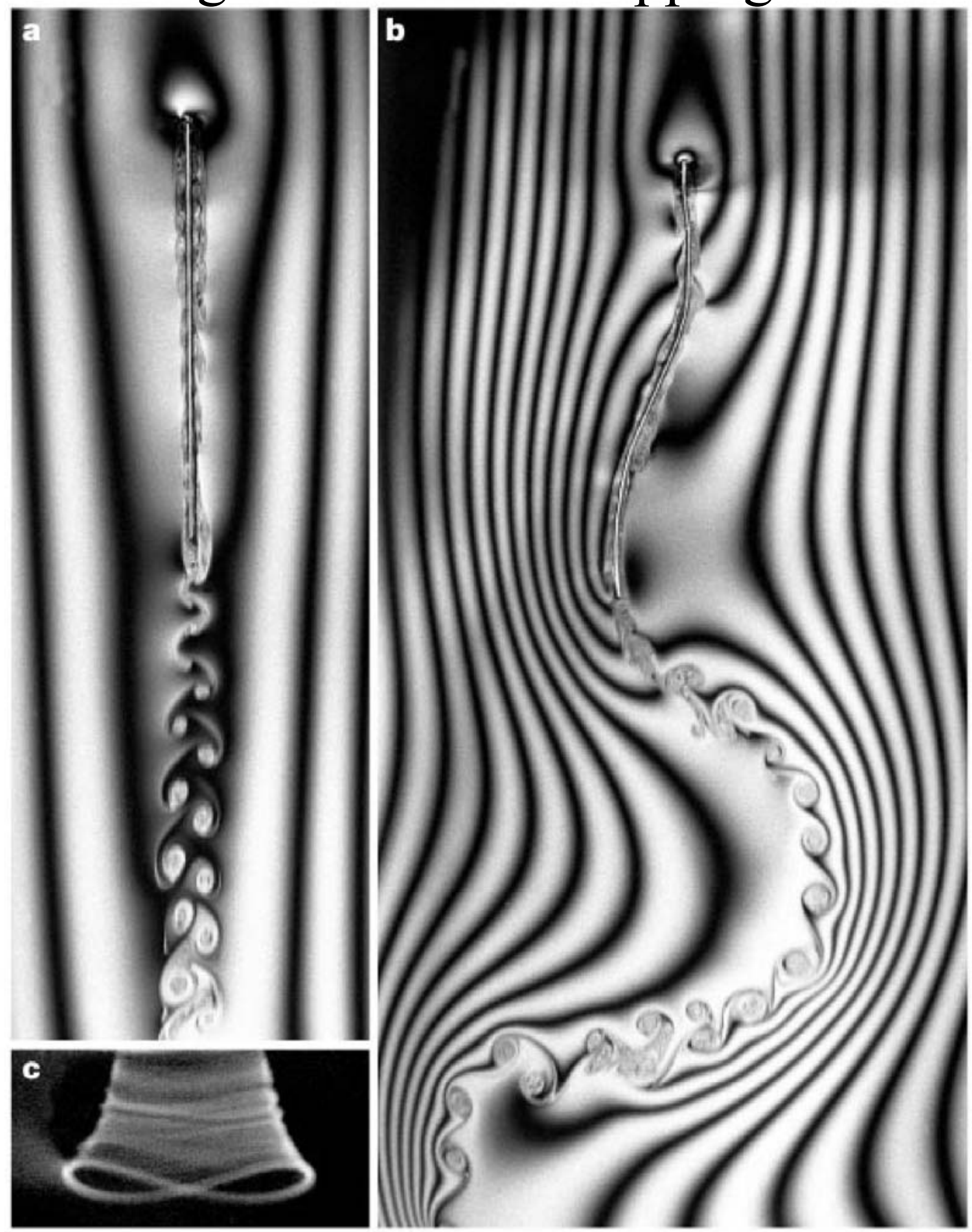
U=1-3 m/s, L=1-4 cm, Re ~ 10^4
bistable and hysteretic
apparent long-wave instability



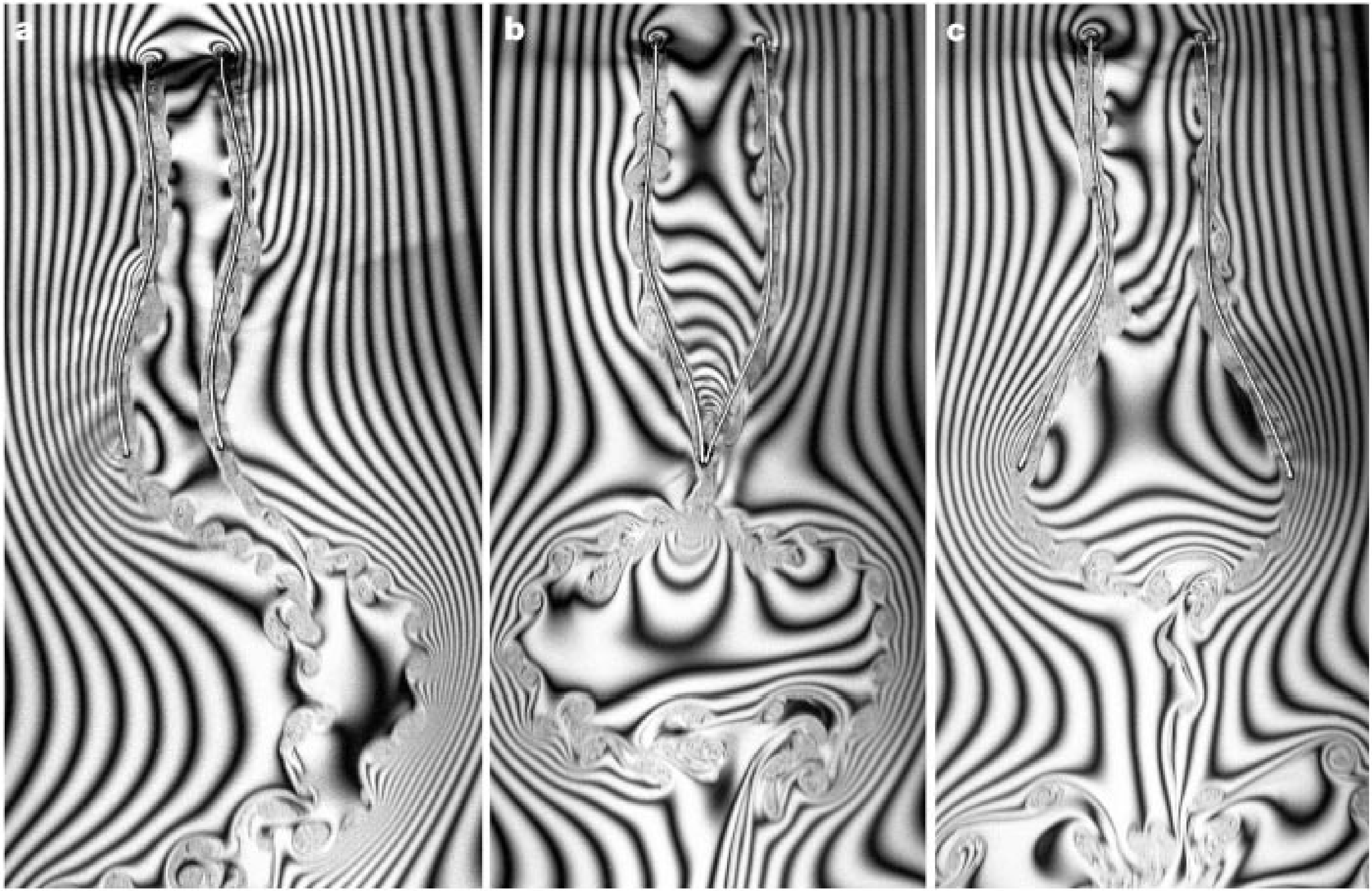
Much much work in past decade:
See **Shelley & Zhang**
Ann. Rev. Fluid Mech. 2011

straight

flapping

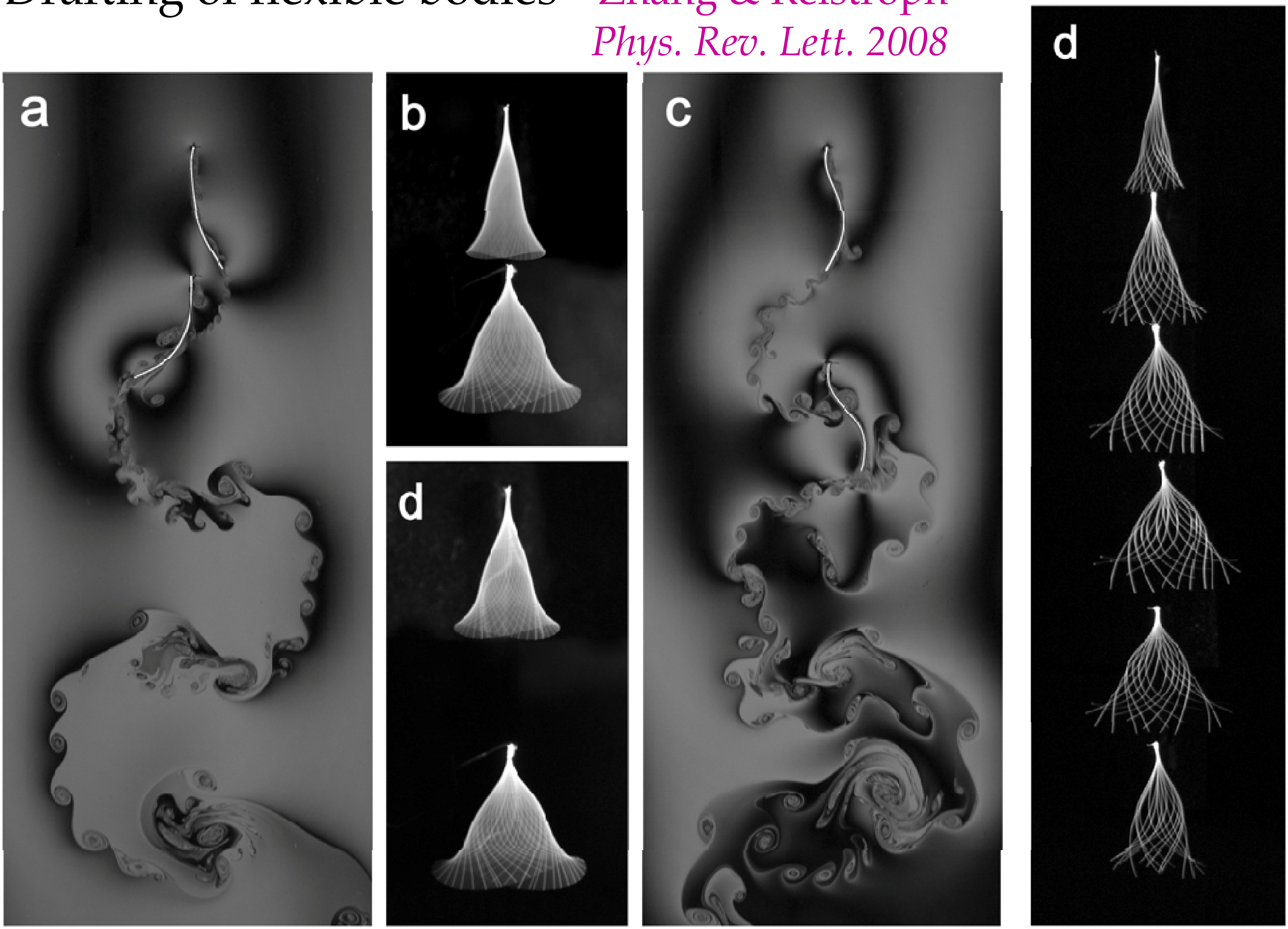


Flexible body-body coupling…

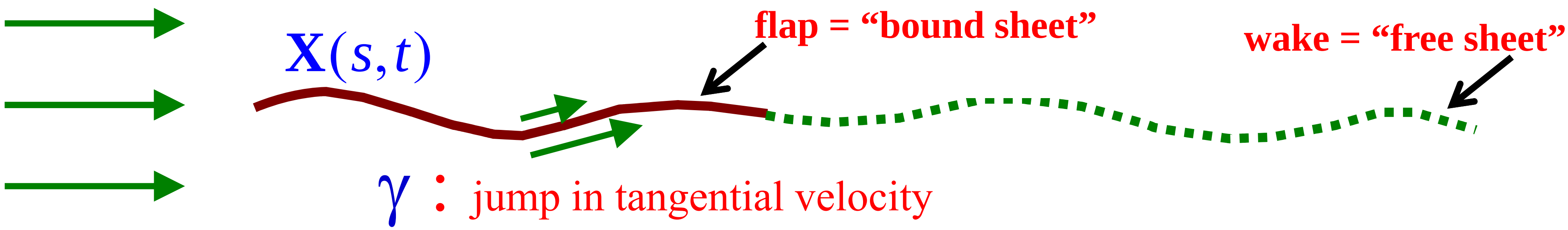


Drafting of flexible bodies – Zhang & Reistroph

Phys. Rev. Lett. 2008



A hydrodynamical model -- flag as a surface of discontinuity (vortex sheet) under stress.



An *exact* reduction of the Euler Eqns to the dynamics of $\boldsymbol{X}(s,t)$

$$\mathbf{X}_t = U\,\mathbf{X}_s^{\perp} + V\,\mathbf{X}_s$$ kinematic BC

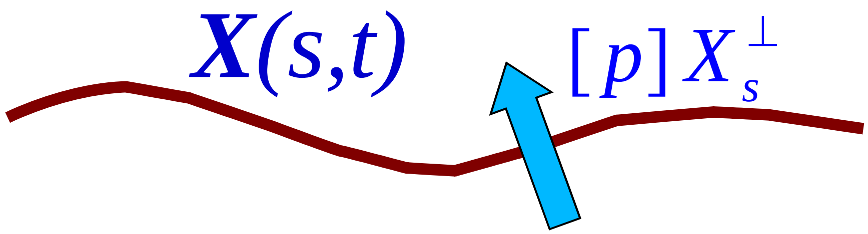
$$\gamma_t = \left(\gamma\left(\mathbf{W}\cdot\mathbf{X}_s - V\right)\right)_s + [p]_s = 0$$ vorticity tranport and production

with $U = \mathbf{W}\cdot\mathbf{X}_s^{\perp}$ normal velocity

$$V = \int_0^s U(s')\,\kappa(s')\,ds'$$ choice of frame

and $$\mathbf{W}[\gamma] = \hat{\mathbf{x}} + \frac{1}{2\pi}\int_{-\infty}^{+\infty} \gamma(s')\,\frac{\left(\mathbf{X}(s) - \mathbf{X}(s')\right)}{\left|\mathbf{X}(s) - \mathbf{X}(s')\right|^2}\,ds'$$ Birkhoff -Rott integral (Biot-Savart Law)

What specifies [*p*]? Surface is also an elastic sheet under pressure load



(*inertial = tensile + bending + pressure*) forces

$$S_1 \mathbf{X}_{tt} = \left(T\,\mathbf{X}_s\right)_s - S_2\,\mathbf{X}_{ssss} + [p]\,\mathbf{X}_s^{\perp}$$

$$S_1 = \frac{mL}{\rho f L^2} \quad \& \quad S_2 = \frac{E/L}{\rho f L^2 U^2}$$

$$= \frac{\text{mass of flag}}{\text{mass of fluid}}; \qquad = \frac{\text{potential elastic energy}}{\text{fluid kinetic energy}}$$

Linear Theory: $\mathbf{X} = (x, \varepsilon\,\eta(x,t))$ with $\varepsilon << 1$

Consider spatially periodic solutions $\Rightarrow$ η satisfies the *IDE*:

$$(\partial_t + \partial_x)^2 \eta = \frac{1}{2} H\left[S_1 \eta_{xtt} - S_2 \eta_{xxxxx}\right] \quad \text{with} \quad H[f](x) = \frac{1}{\pi} P \int_{-\infty}^{+\infty} \frac{f(y)}{x-y}\, dy$$

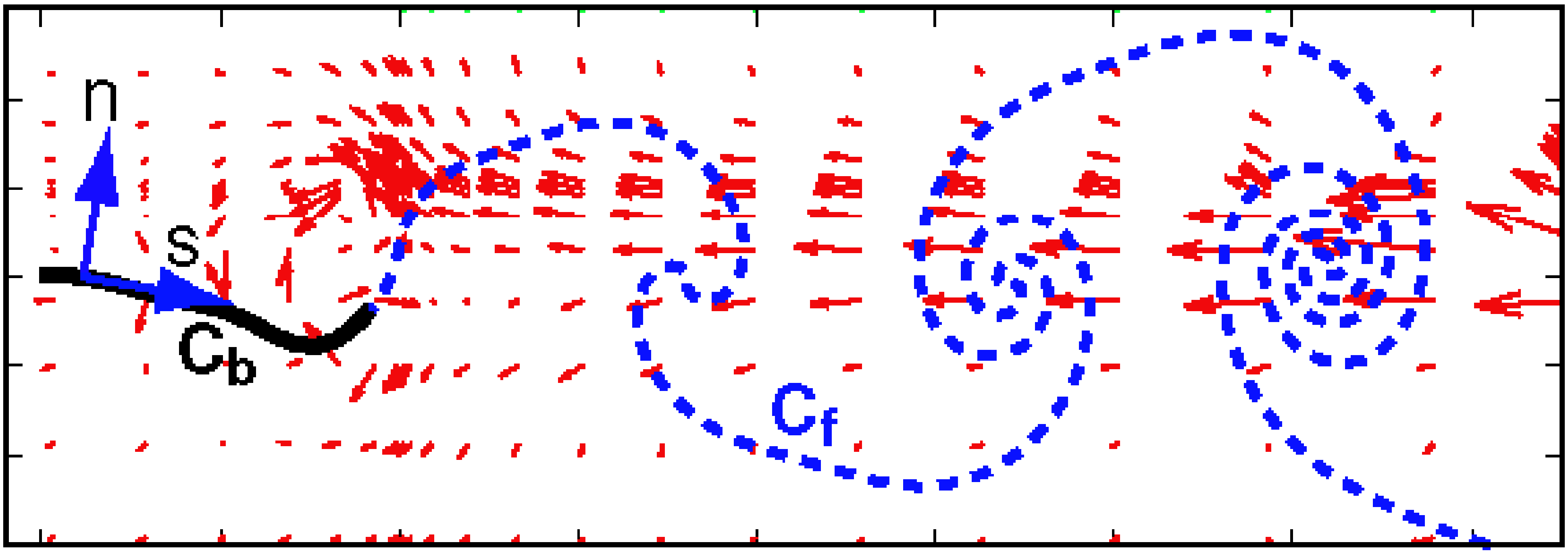
$$\eta = e^{i(\omega t + kx)}$$

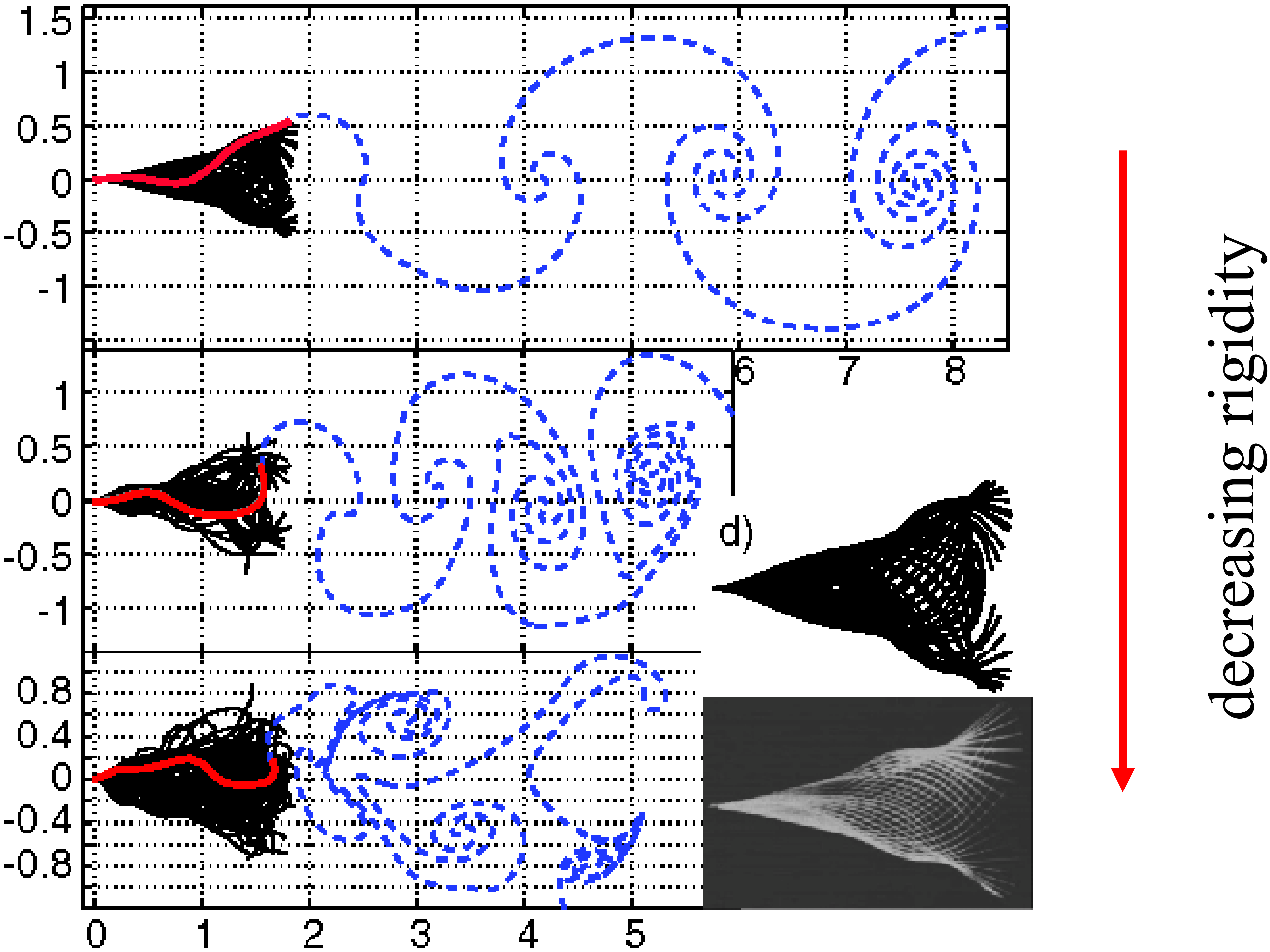
$$\Rightarrow \quad \omega = \frac{-k}{1 + (1/2) S_1 |k|}\left[1 \pm (1/2)|k|^{1/2} \overbrace{\left(S_1 S_2 |k|^3 + 2 S_2 |k|^2 - 2 S_1\right)^{1/2}}^{d_k}\right]$$

- $S_1 > 0,\ S_2 = 0$ $\Rightarrow$ *Unstable at all scales*
- $S_1 = 0,\ S_2 > 0$ $\Rightarrow$ **no flag mass,** *only dispersive waves.*
- $d_1 = S_1 S_2 + 2 S_2 - 2 S_1 = 0$ gives stability exchange for fundamental mode

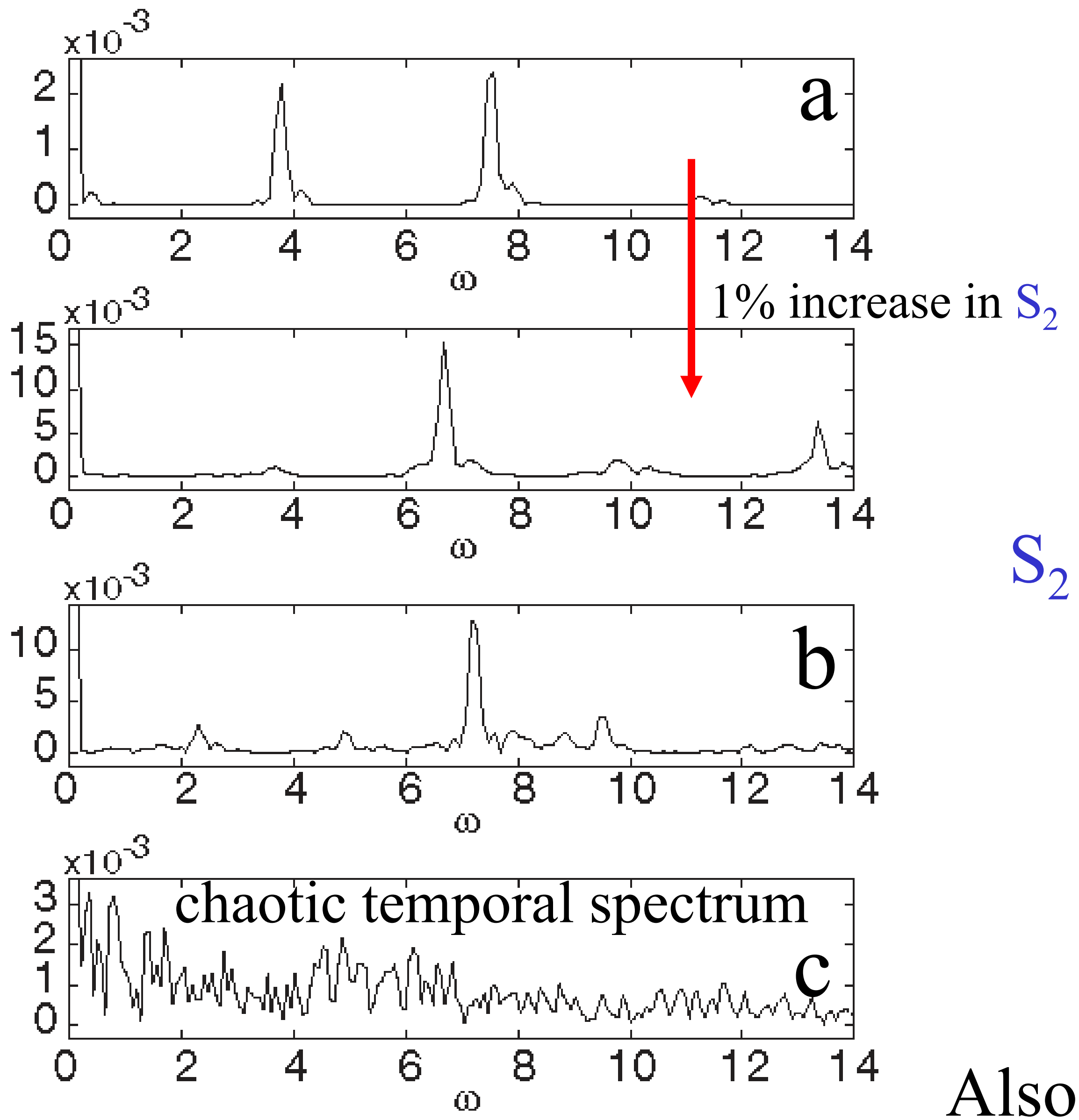
(Huang '95 numerically solves linearized finite flag w. wake)

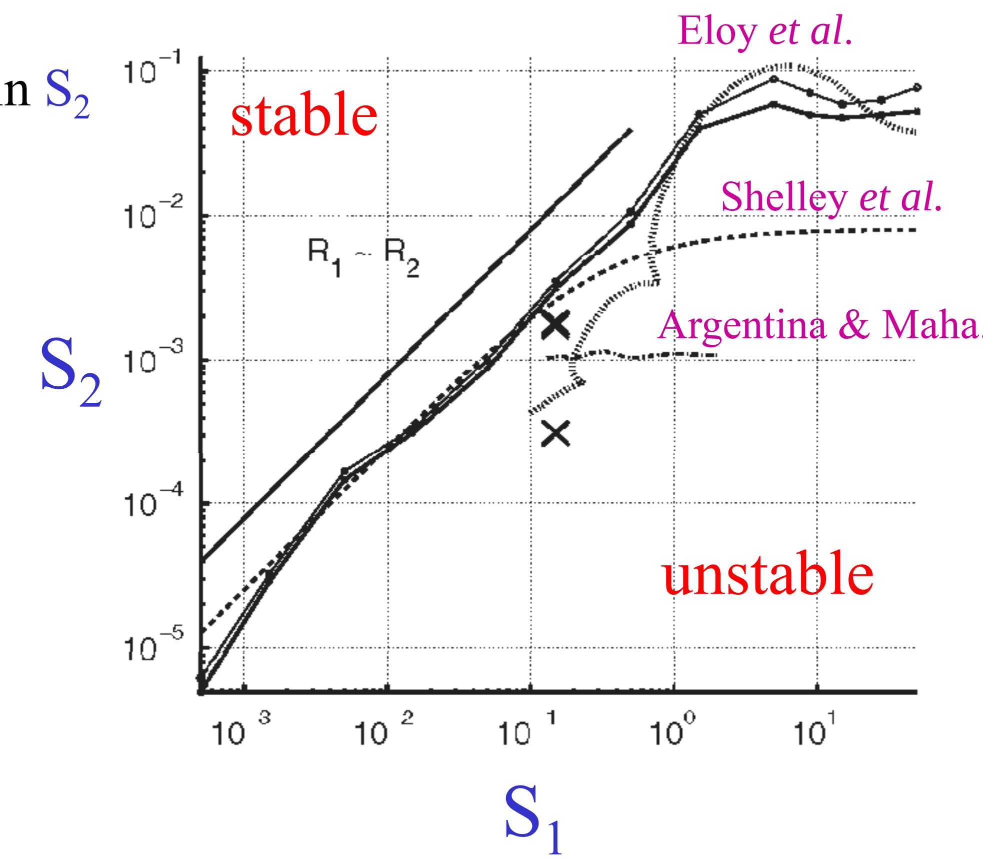
Alben & Shelley, *PRL* 2008 – flag as slip surface (bound vortex sheet) shedding a free vortex sheet (ala Krasny 90's; Jones & Shelley JFM '05, …)
Shedding rate determined by condition of bded velocity at free end.



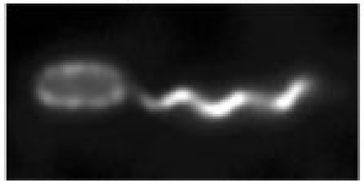

1.5
1
0.5
0
-0.5
-1
6
7
8
0.8
0.4
-0.4
-0.8
0
1
2
3
4
5
d)
decreasing rigidity

Shows sensitivity of frequency content to S_2, and appearance of more spatial and temporal degrees of freedom





Also observe bistability …



non-reciprocal waves

Re << 1

Micro-organisms and birds (or fish) use very different locomotion strategies

Some organisms live between these worlds

clione antarctica

Childress and Dudley *JFM* 2004

switches strategies with adulthood:
rowing cilia to flapping wings

Re ~ 10

Reciprocal flapping

Re >> 1

Question: Is there some decisive change in the way a fluid and a "free" body interact as *Re* increases?

Navier-Stokes Eqs:

$$Re\left(\partial_t \mathbf{u} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \Delta\mathbf{u} \quad \& \quad \nabla\cdot\mathbf{u} = 0$$

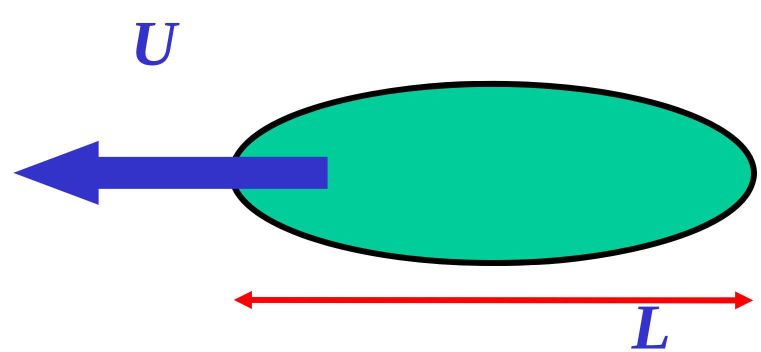
Reynolds Number: $Re = \dfrac{\rho U L}{\mu}$

$\rho =$ fluid density

$\mu =$ viscosity

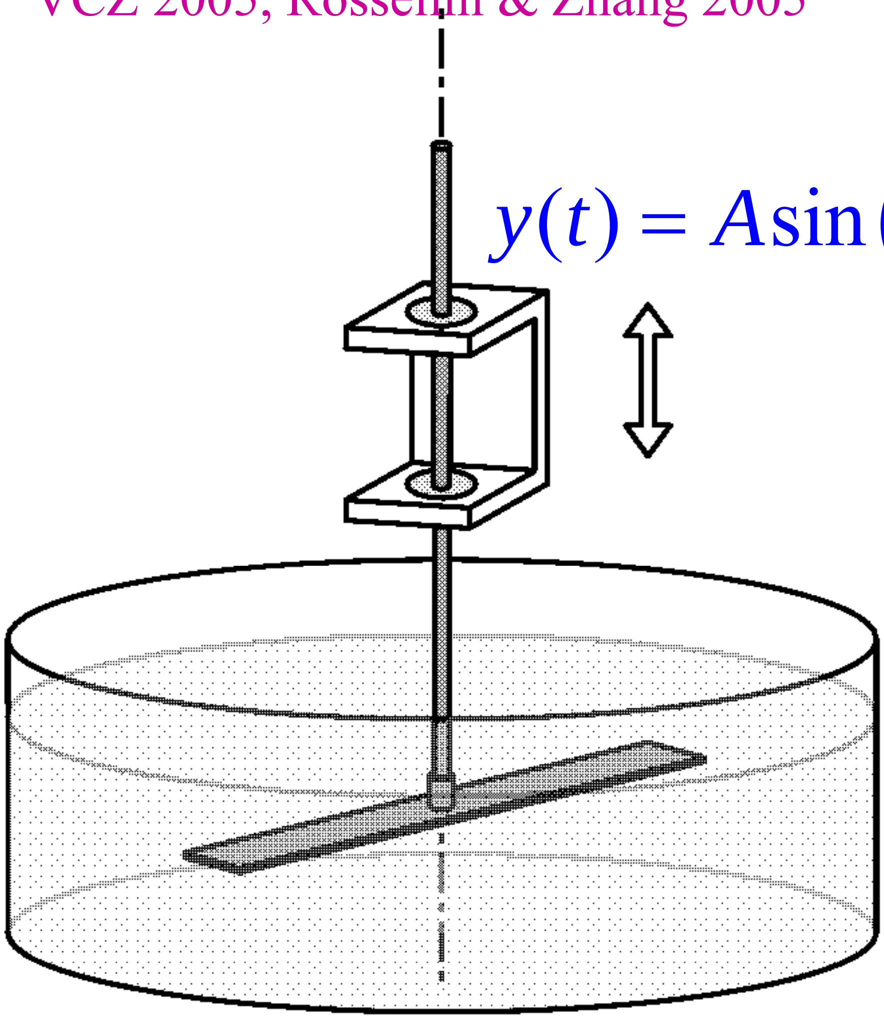
$U =$ characteristic velocity

$L =$ characteristic length

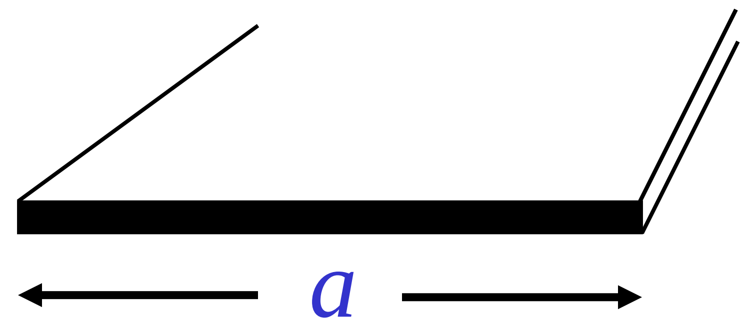


Rotary Reciprocal Flapper Experiment

Vandenberghe, Zhang, and Childress, *JFM* 2004,
VCZ 2005, Rosselini & Zhang 2005



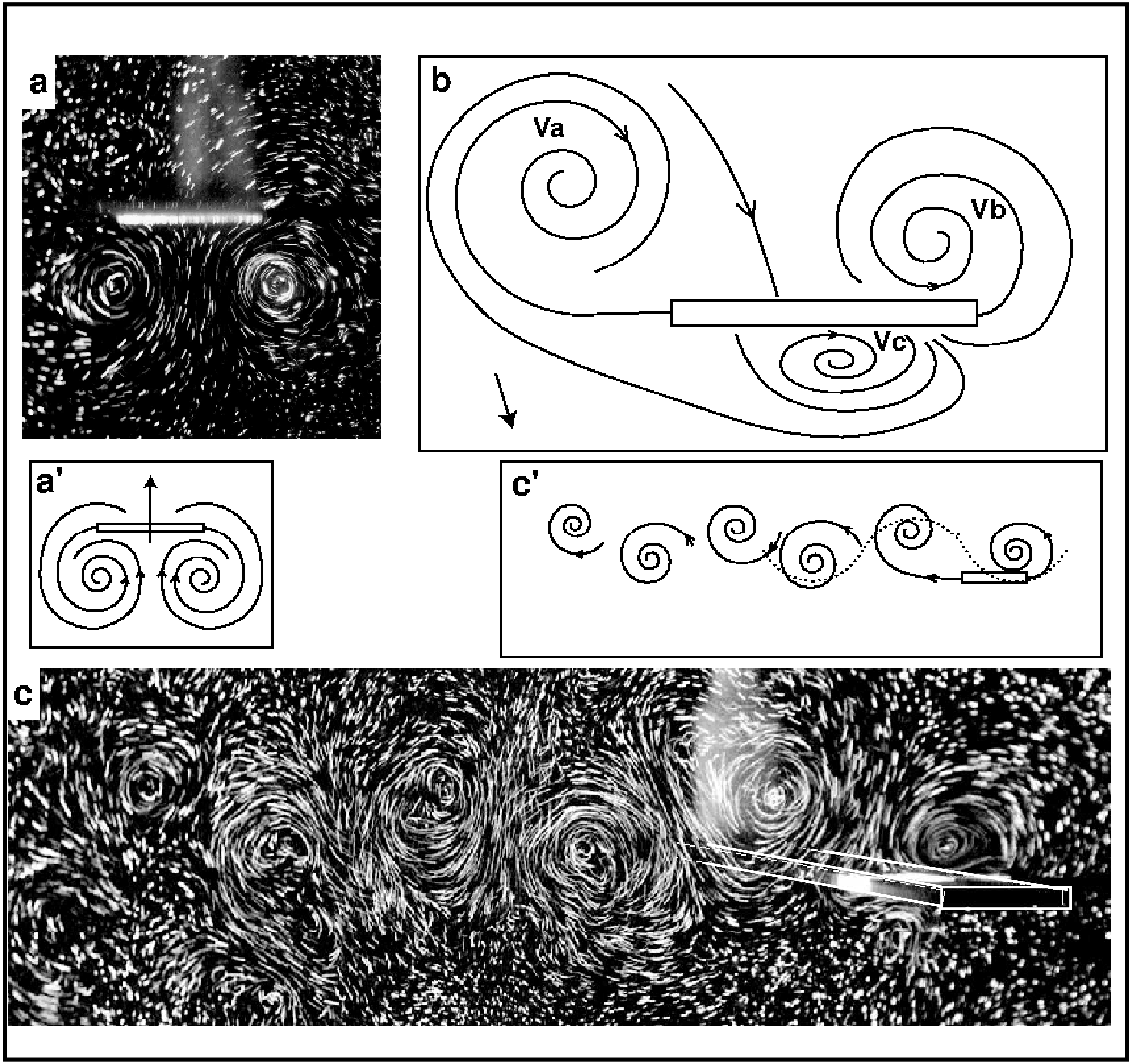
$$y(t) = A\sin(2\pi f t)$$

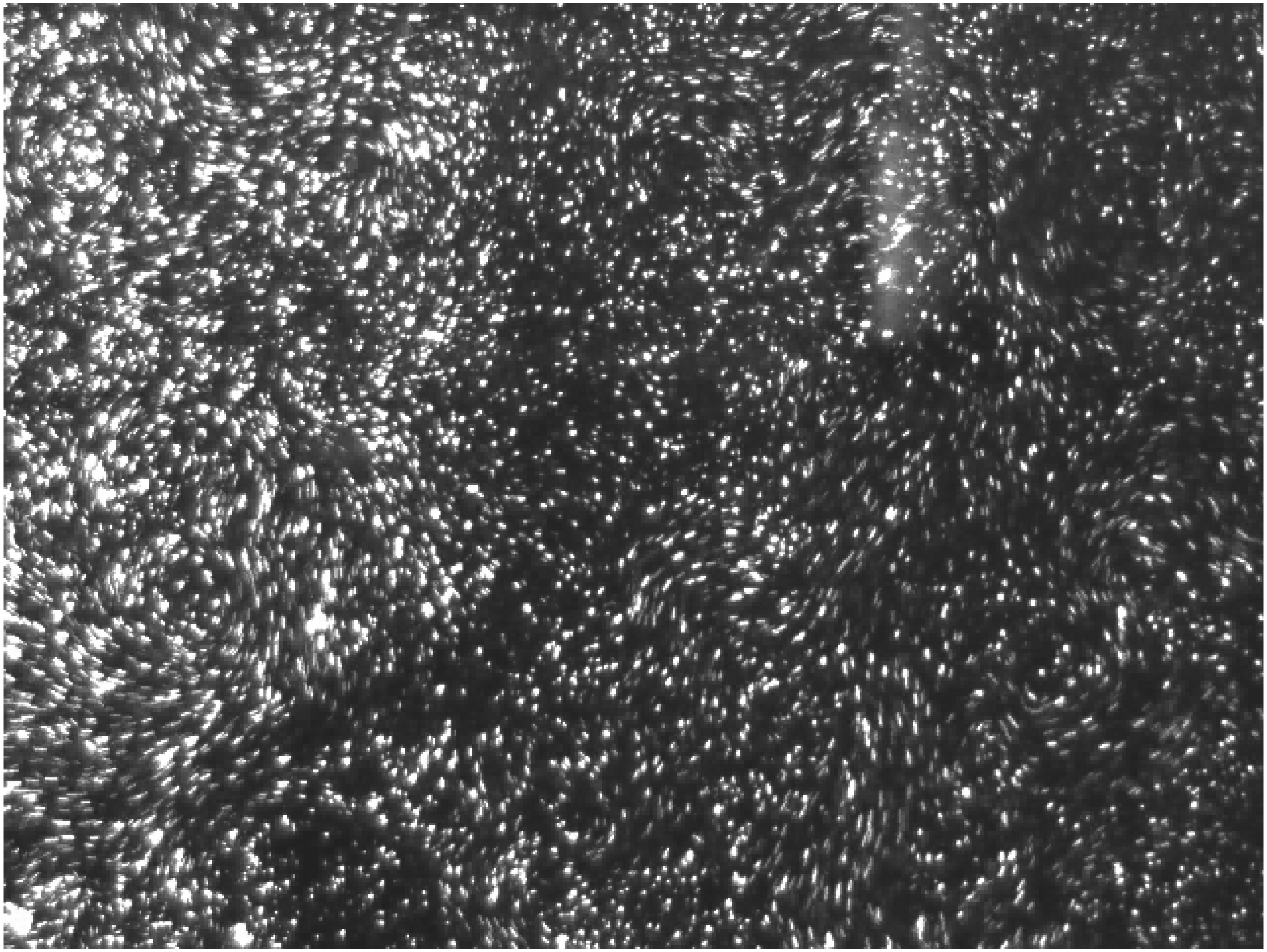


$$Re_{fr} = \frac{\rho \cdot fA \cdot a}{\mu}$$

= frequency Reynolds number

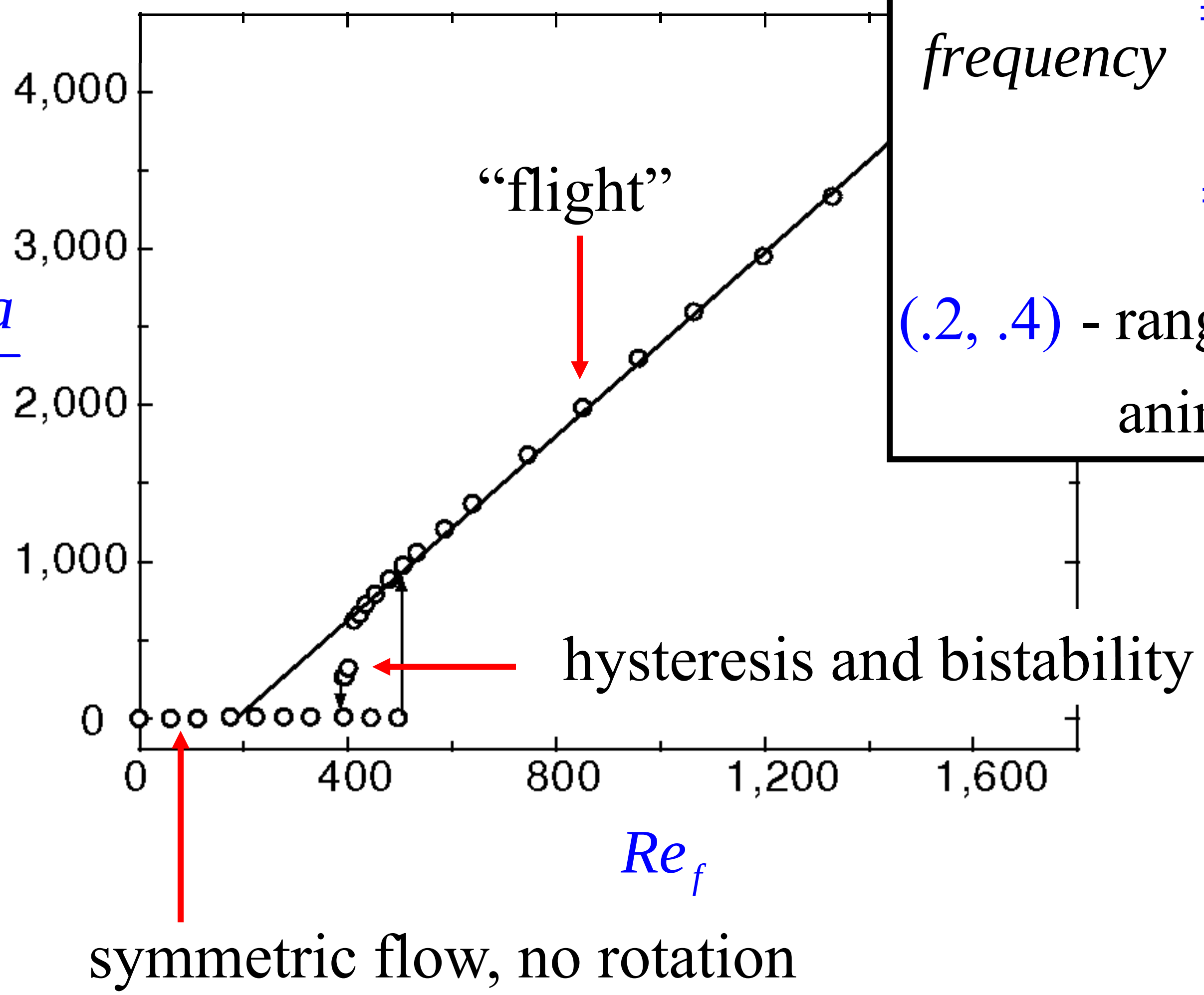
"wing" free to rotate – in either direction


a
b
Va
Vb
Vc
a'
c'
c



Rotational speed versus driving frequency

$$Re_\Omega = \frac{\rho(3d\Omega/4)a}{\mu}$$



Strouhal frequency $= \frac{Re_f}{Re_\Omega} = \frac{2Af}{U} = 0.26$

(.2, .4) - range of efficient animal swimming

Extrapolating out bearing friction: $Re_{fr}^{crit} \sim 20-50$

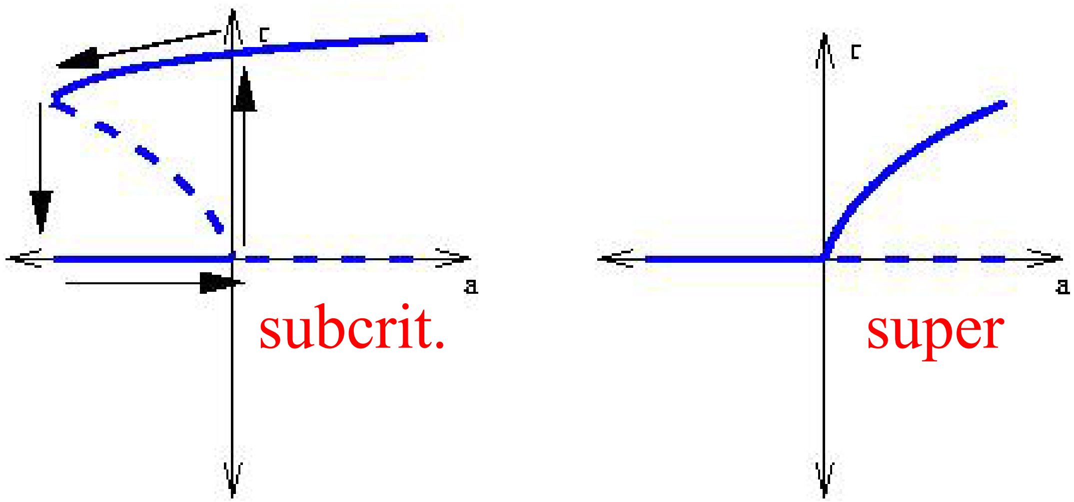
Questions from the experiment...

- What is the true nature of the bifurcation, subcritical or supercritical?

  Friction on axle is a confounding factor.

  Extrapolation with increasing viscosity:

  $$Re_f^{crit} \sim 20 - 50$$

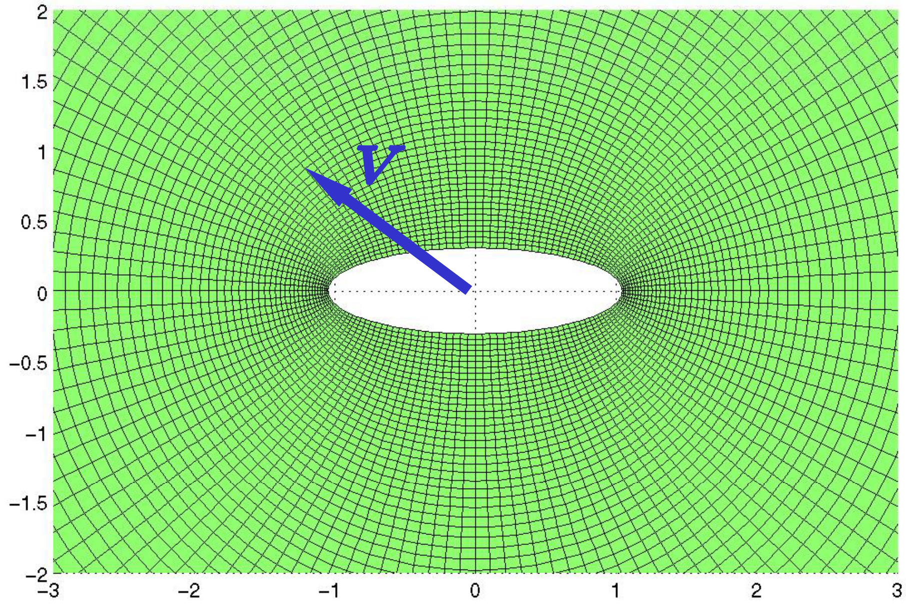


- What does the work, pressure or viscous forces, as the wing "takes off"?

- Is it really so easy? What is the role of the body mass? Body shape?

Simulate the dynamics of a 2D flapping elliptical body

Alben & Shelley, PNAS 2005



(also, Z.-J. Wang, '99, '00)

vorticity $\omega = \mathbf{k}\cdot(\nabla\times\mathbf{u})$

$$\begin{cases} Re\,(\partial_t\omega + \mathbf{u}\cdot\nabla\omega) = \Delta\omega \\ \mathbf{u} = \nabla^{\perp}\psi \quad \& \quad \Delta\psi = -\omega \end{cases}$$

(Navier-Stokes in vorticity-stream variables)

BCs in body frame:

On the body surface $\begin{cases} \psi = Const & \text{(no penetration)} \\ \partial_n\psi = 0 & \text{(no slip)} \end{cases}$

In the far-field $\begin{cases} \omega = 0 \\ \mathbf{u} = -\mathbf{v} \end{cases}$

Simulated using an 2^{nd} – order (implicit) in time,

In space, mixed Fourier/finite differences, 4^{th} – order method

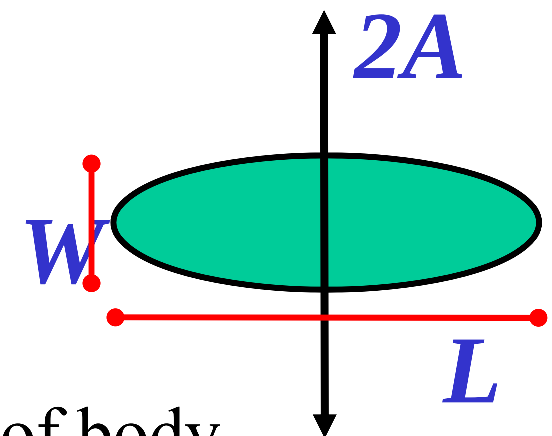
Determining $\mathbf{v} = (v_x, v_y)$: $v_y = (2\pi fA)\cos(2\pi ft)$

- Find v_x by Newton's 2nd Law:

$$M\, Re_{fr} \frac{dv_x}{dt} = \hat{\mathbf{x}} \cdot \mathbf{F}_{fluid} \quad \text{with} \quad \mathbf{F}_{fluid} = \int_{body} [-p\mathbf{I} + 2\mathbf{E}]\mathbf{n}\, ds$$

Invariant: $M\, v_x + \int \hat{\mathbf{x}} \cdot \mathbf{u}\, dA$

the total horizontal momentum



- Parameters:

$$Re_{fr} = \frac{\rho \cdot fA \cdot L}{\mu}$$

$$M = \frac{\rho_{body}}{\rho_{fluid}} \frac{Area}{L^2}$$

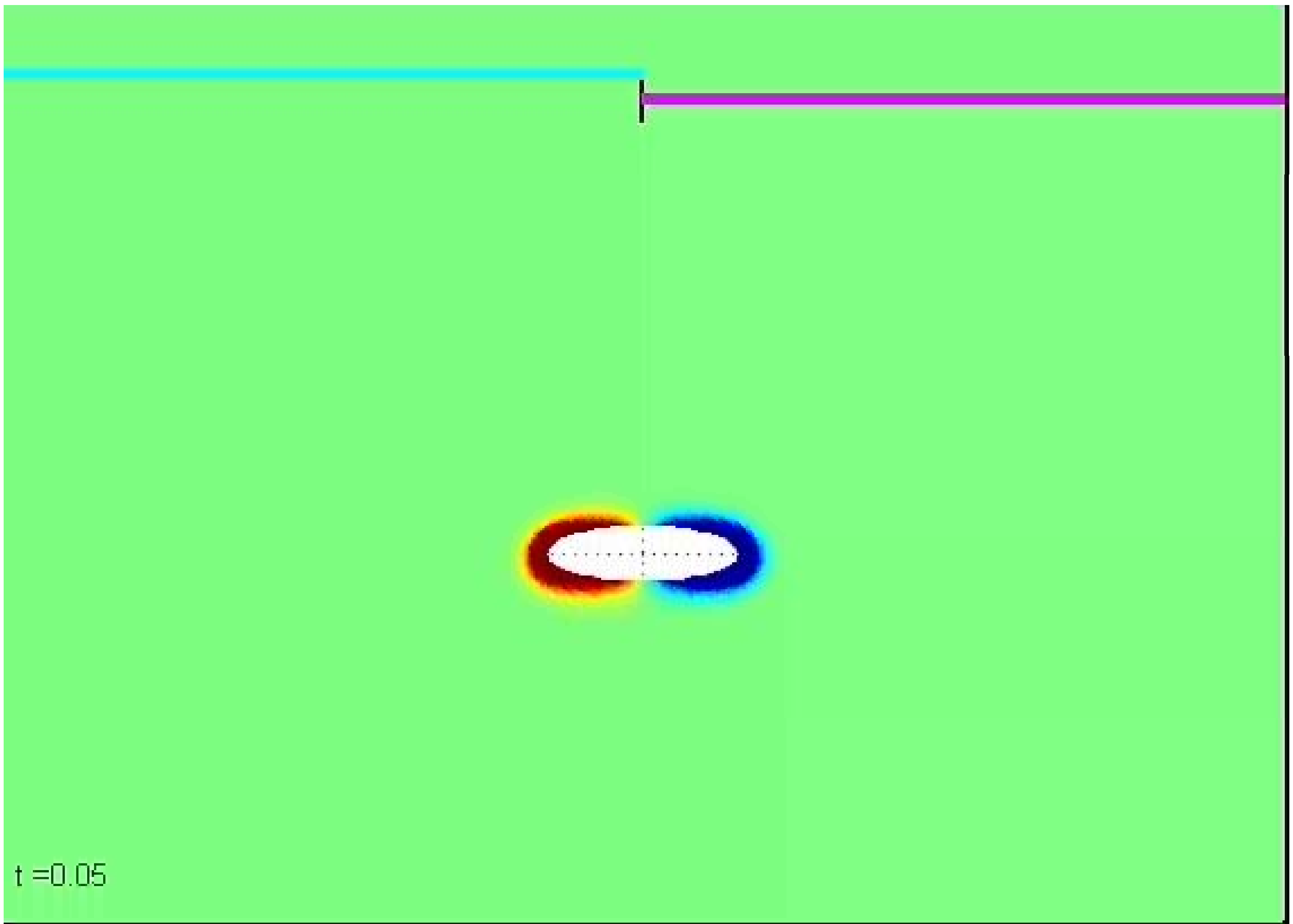
= effective mass

$\frac{L}{W}$ aspect ratio of body

$\frac{A}{L}$ chord-to-amplitude ratio (set to 1/2)

“low” Reynolds number flapping

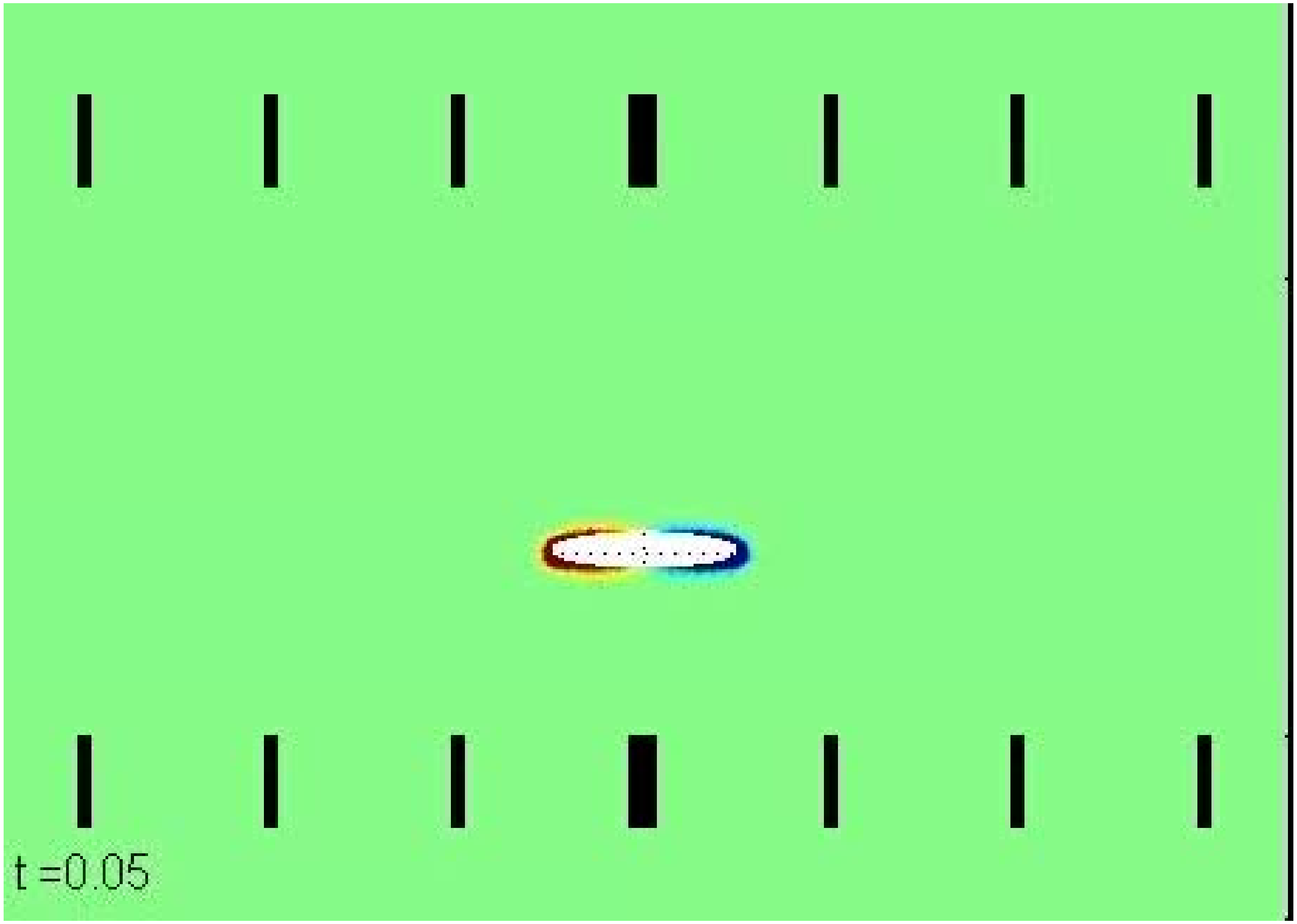
$$\mathrm{Re}_{fr} = 7, \quad M = 1, \quad L/W = 3$$



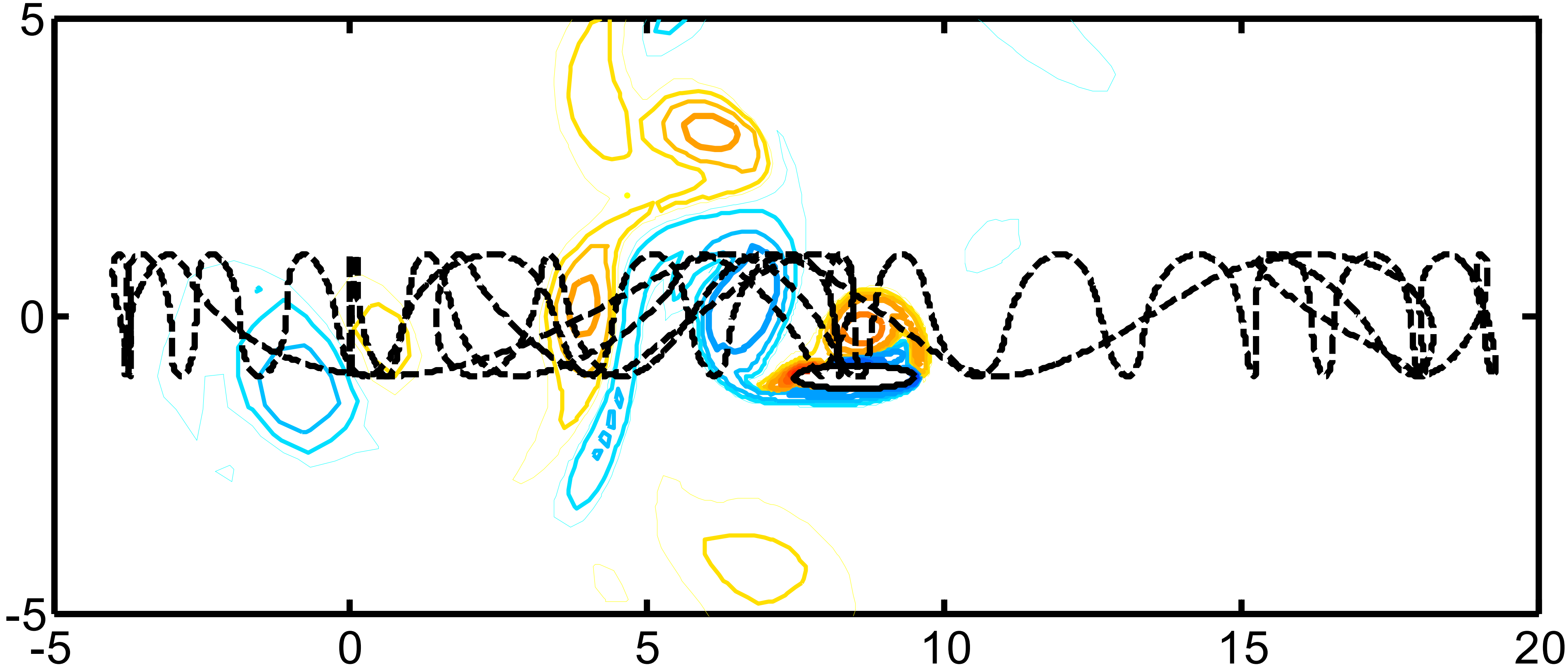
Symmetric fluid response

A faster body …

$$Re_f = 35, \;\; \rho_b / \rho = 1, \;\; L/W = 5$$

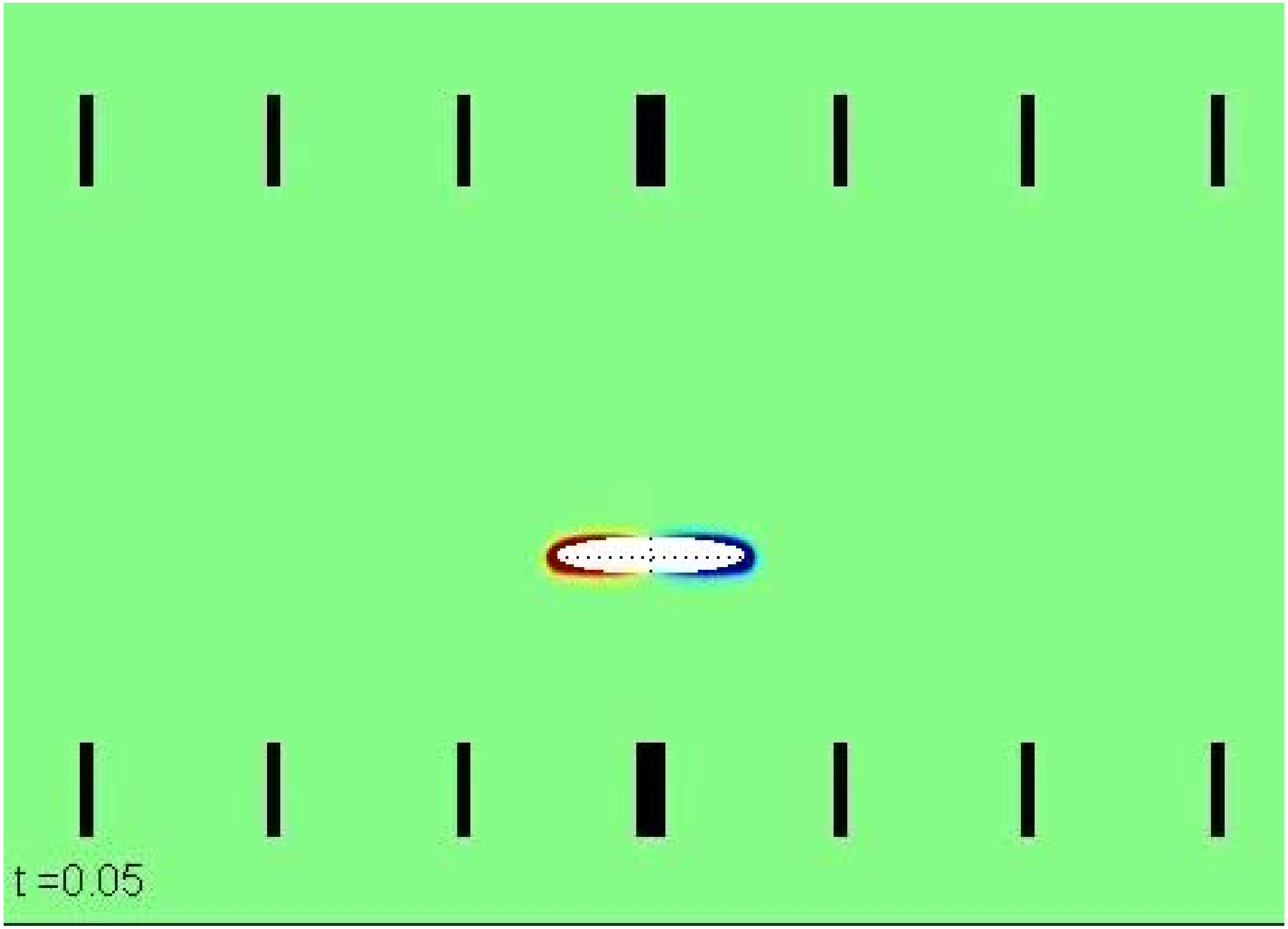


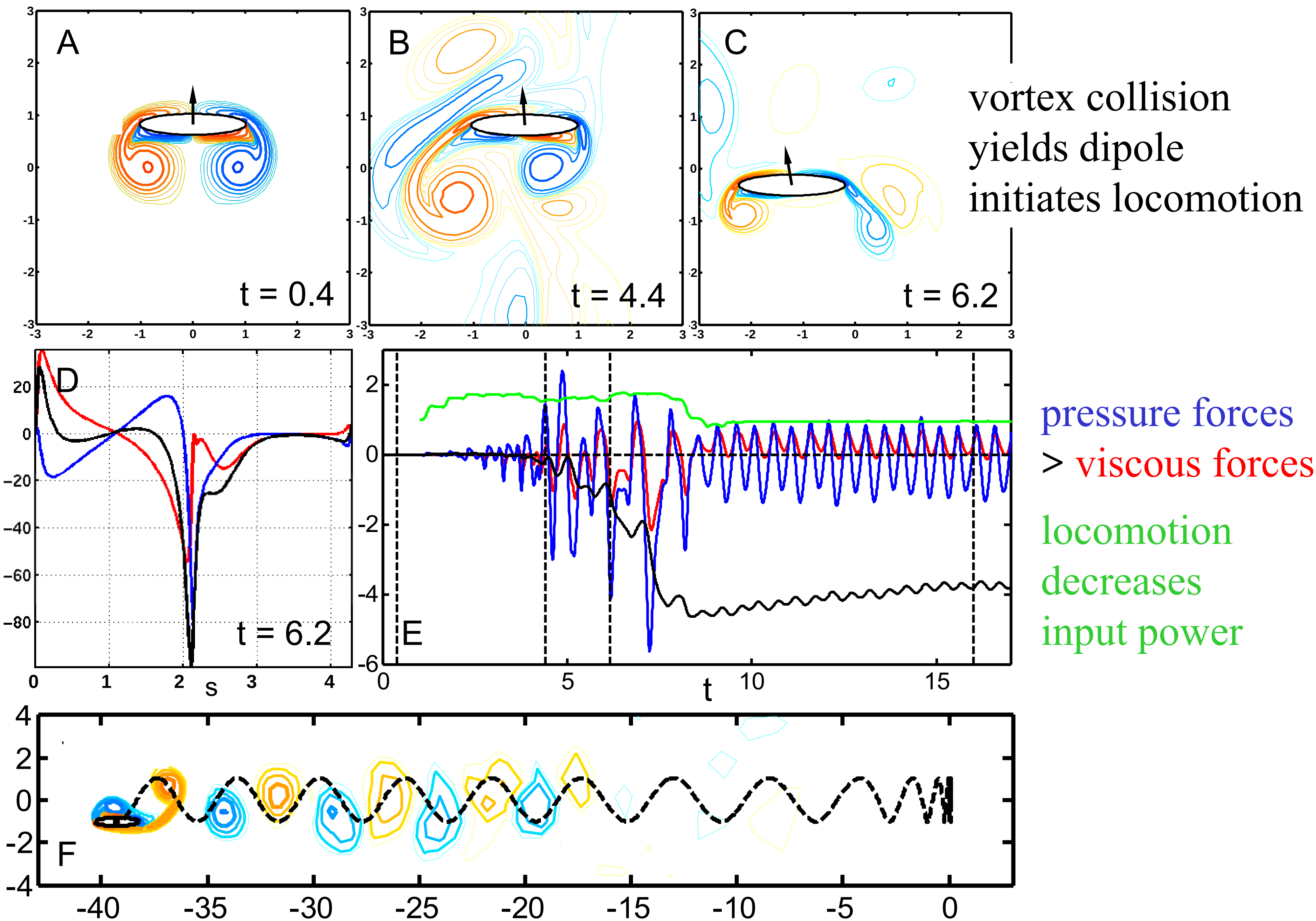
Swimming? Chaotically perhaps



let's make the "swimmer" a little heavier …

$$\mathrm{Re}_{fr} = 35, \ \ \rho_b / \rho = 32, \ \ L/W = 5$$

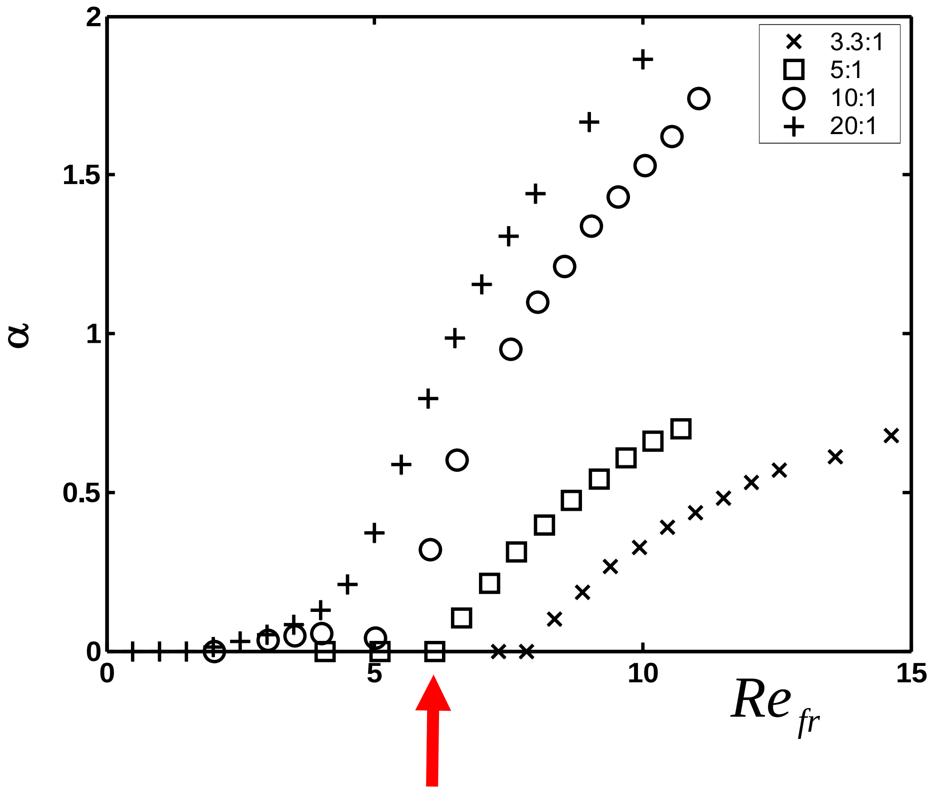


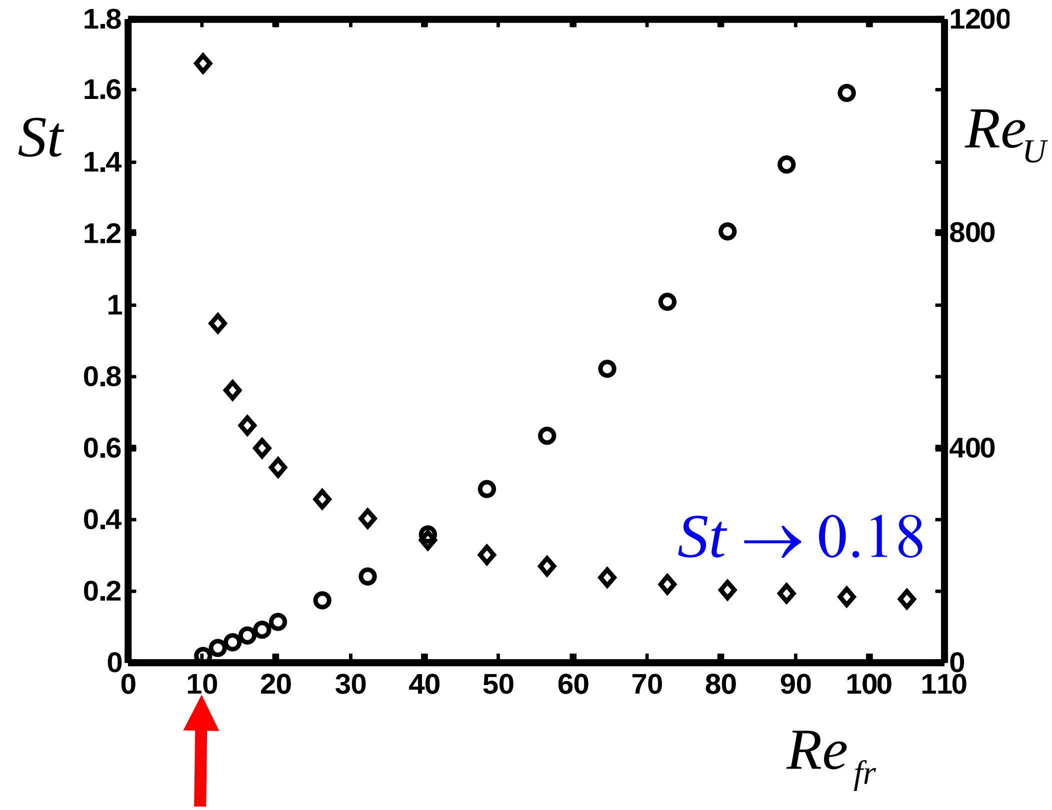


A
t = 0.4
B
t = 4.4
C
t = 6.2
vortex collision
yields dipole
initiates locomotion
D
t = 6.2
s
E
t
pressure forces
> viscous forces
locomotion
decreases
input power
F

Find that $|v_x| \sim e^{\alpha t}$

$Re_U = \dfrac{\rho U L}{\mu}; \quad St = \dfrac{2 Re_{fr}}{Re_U}$





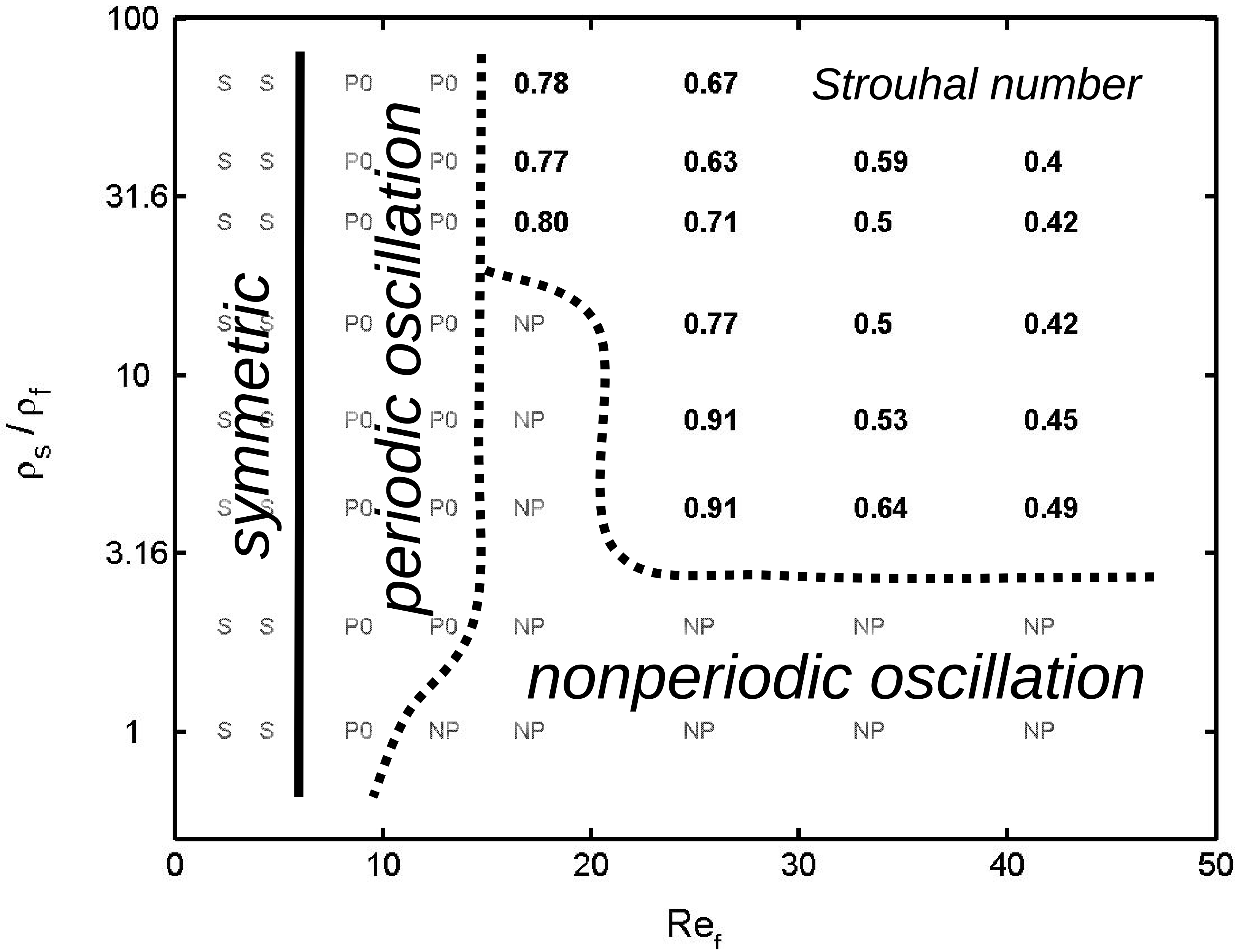
Critical $Re_{fr} \approx 7$

Critical $Re_{fr} \approx 10$

First bifurcation is von Karman instability of a symmetric wake

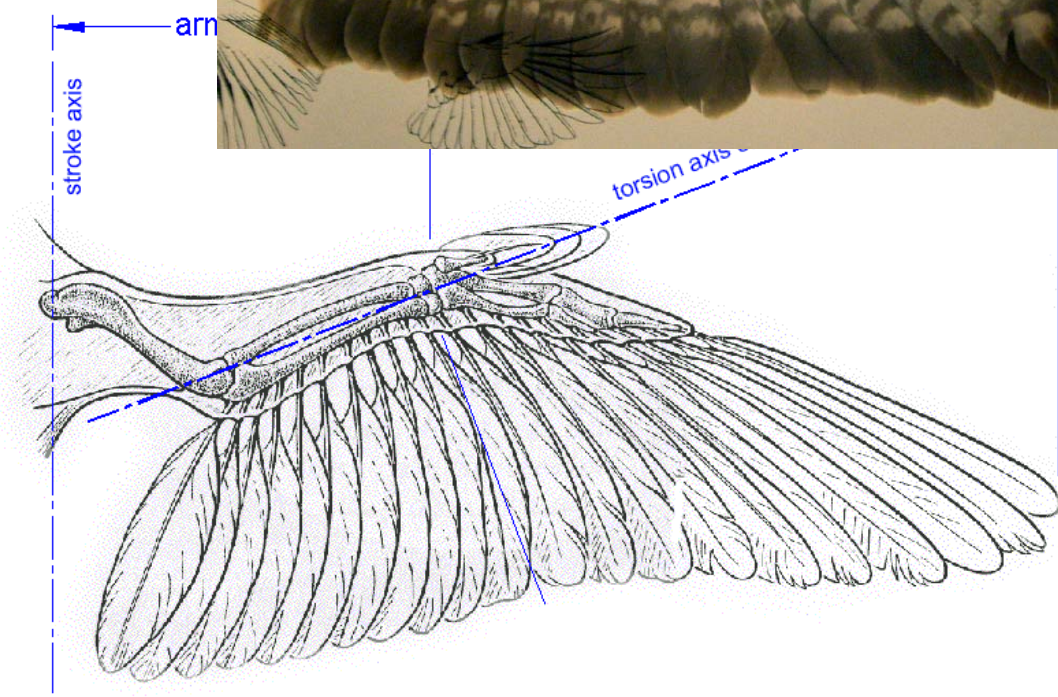
Second is to unidirectional locomotion – looks *supercritical*

St=0.2 - 0.4 typically observed for animal locomotion

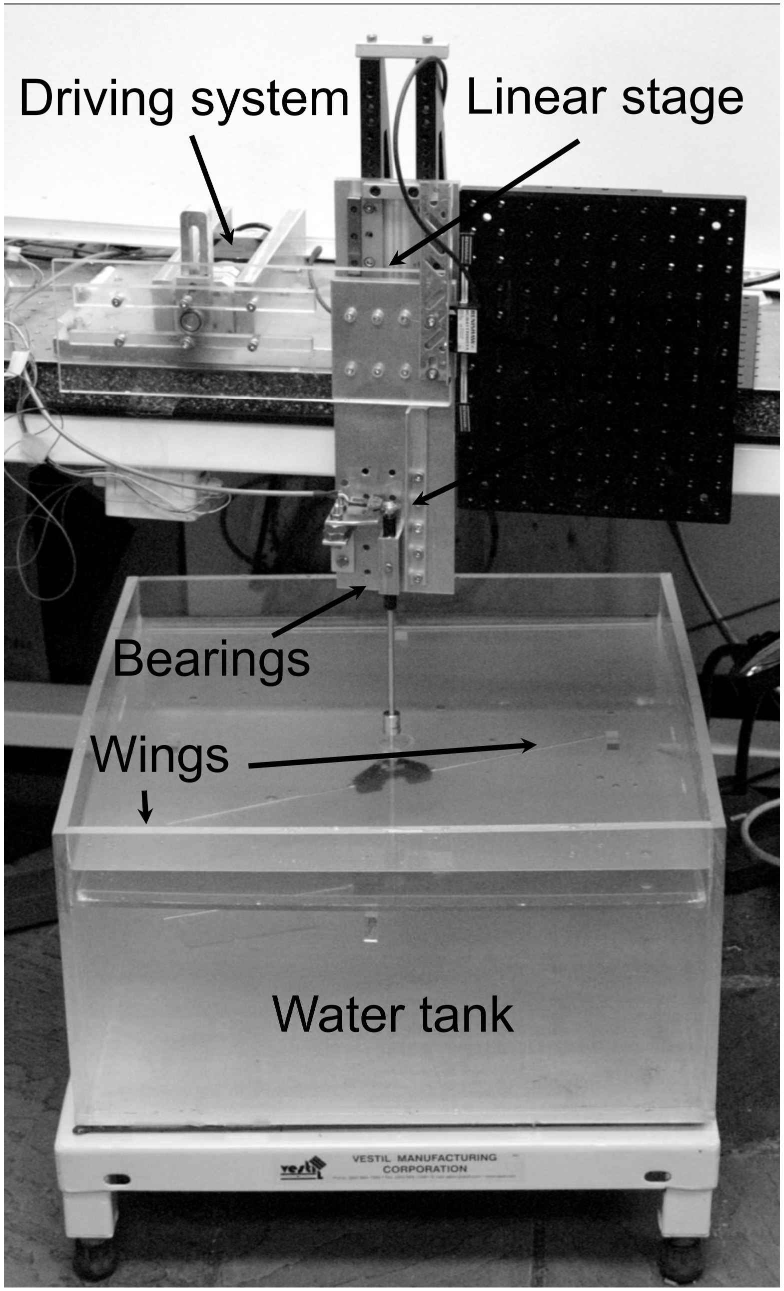

Strouhal number
symmetric
periodic oscillation
nonperiodic oscillation
S S P0 P0 0.78 0.67
S S P0 P0 0.77 0.63 0.59 0.4
S S P0 P0 0.80 0.71 0.5 0.42
S S P0 P0 NP 0.77 0.5 0.42
S S P0 P0 NP 0.91 0.53 0.45
S S P0 P0 NP 0.91 0.64 0.49
S S P0 P0 NP NP NP NP
S S P0 NP NP NP NP NP
100
31.6
10
3.16
1
0
10
20
30
40
50
ρ_s / ρ_f
Re_f

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 or disadvantage to be (somewhat) flexible?

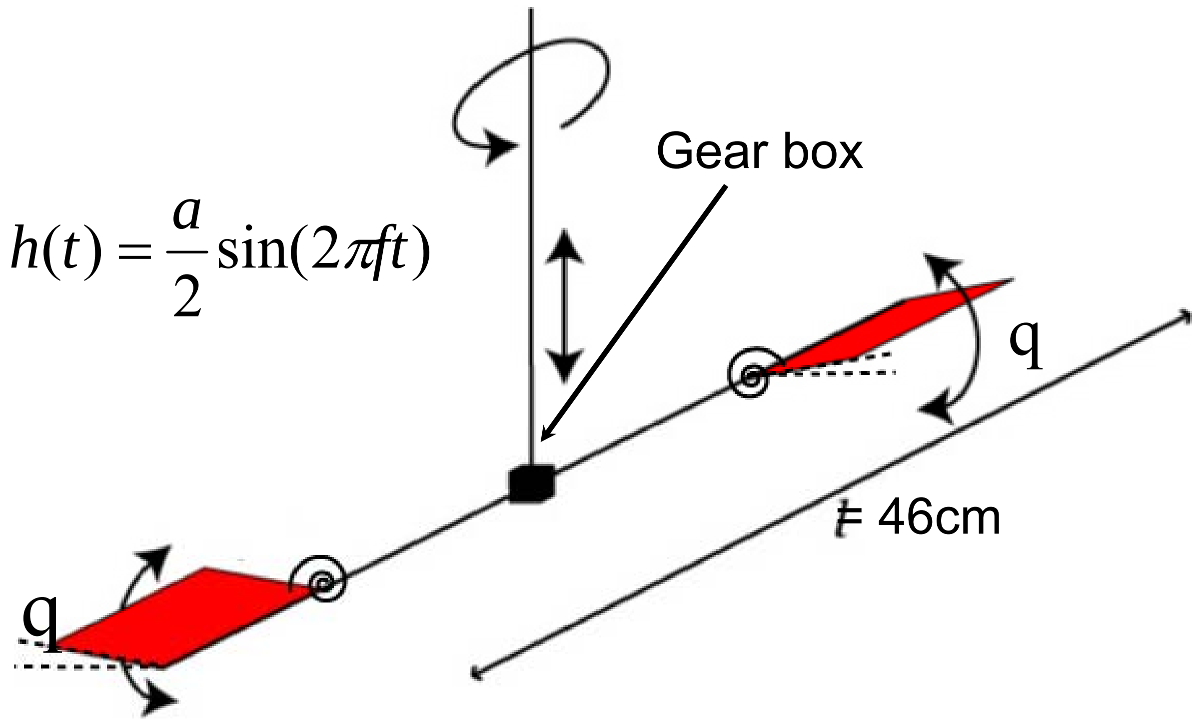


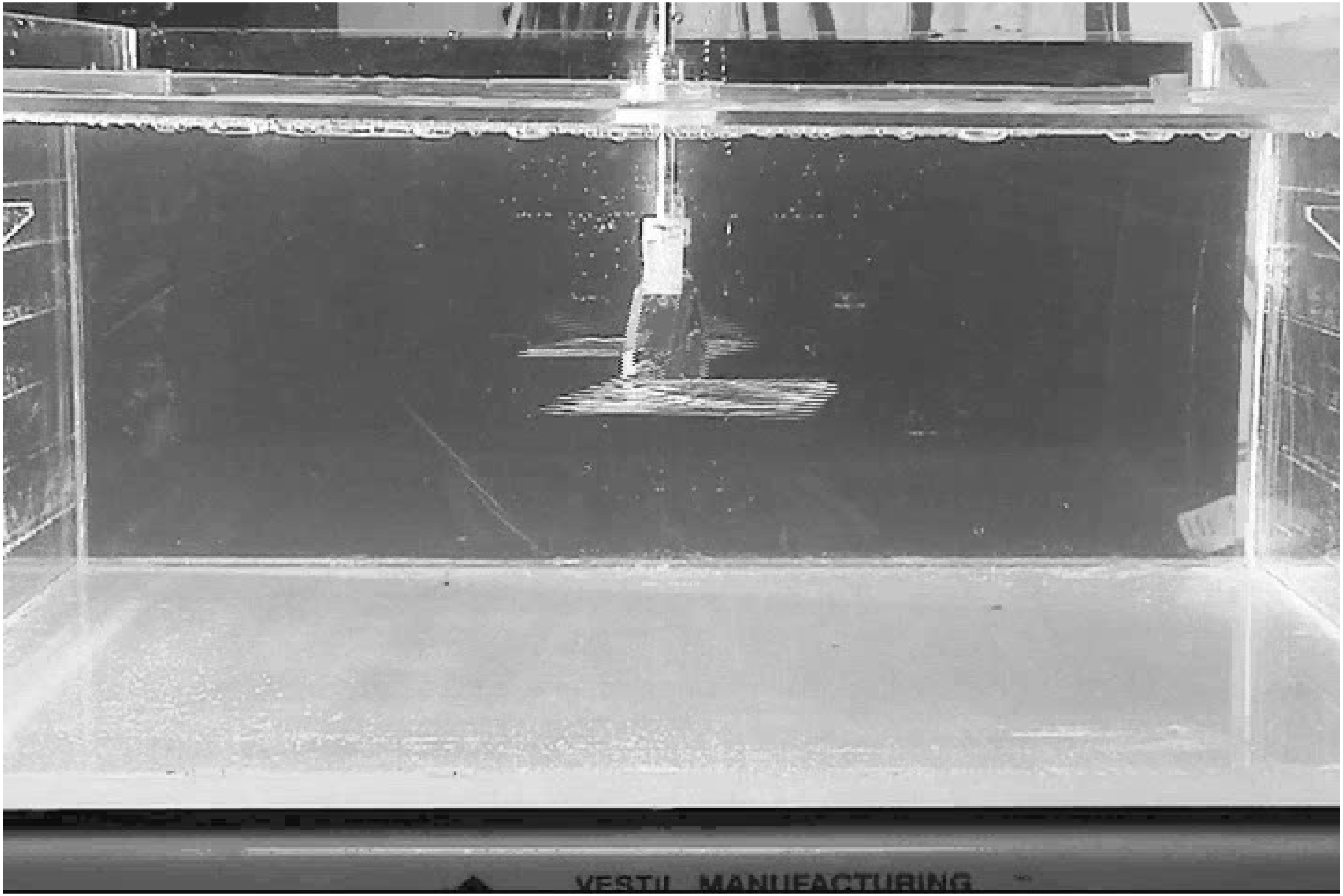
Experimental setup on passive pitching and free flight



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

- 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 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.

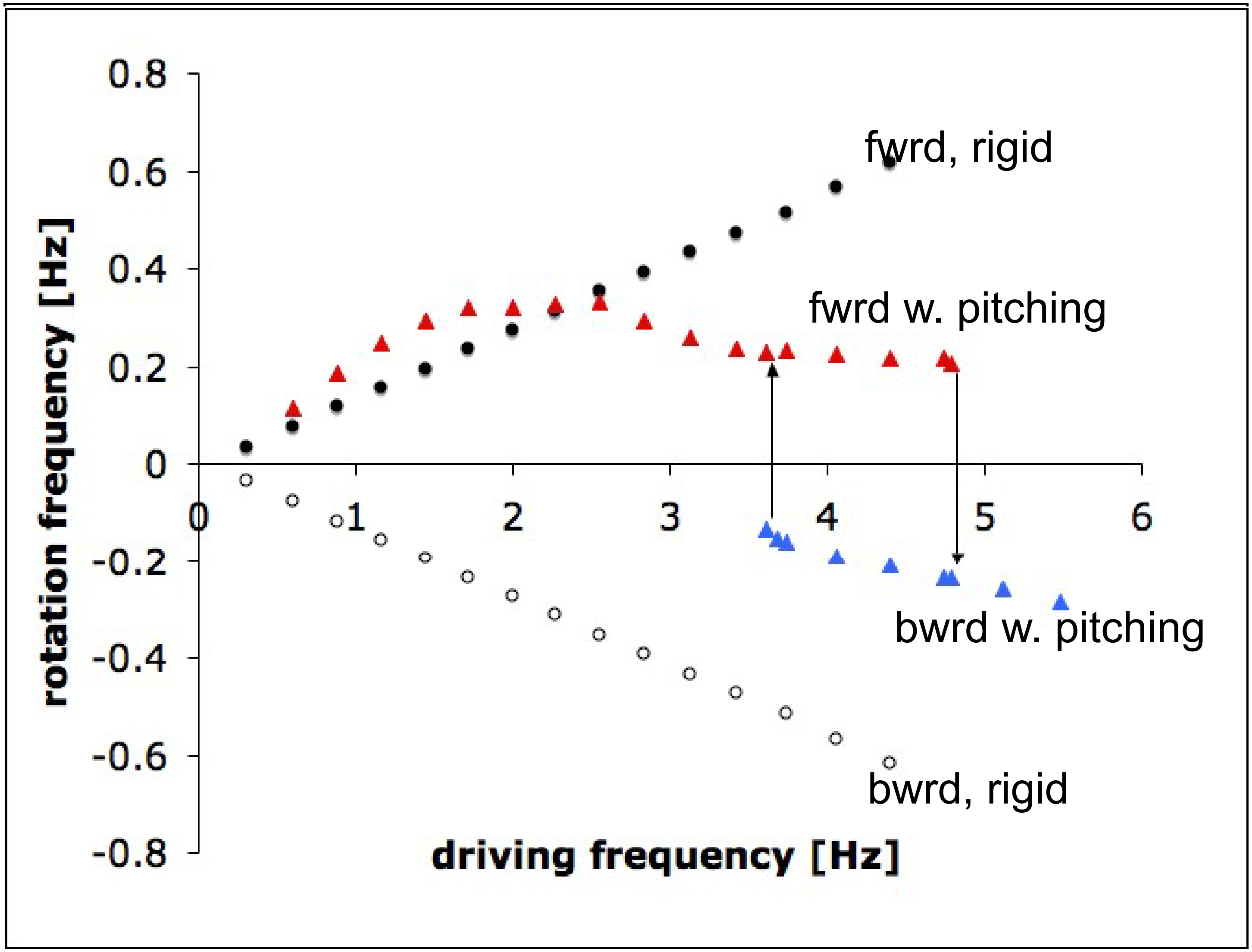
The main effects of passive pitching in free flight

$$\mathrm{Re} = \frac{afc}{\nu} \sim 10^{4-5}$$

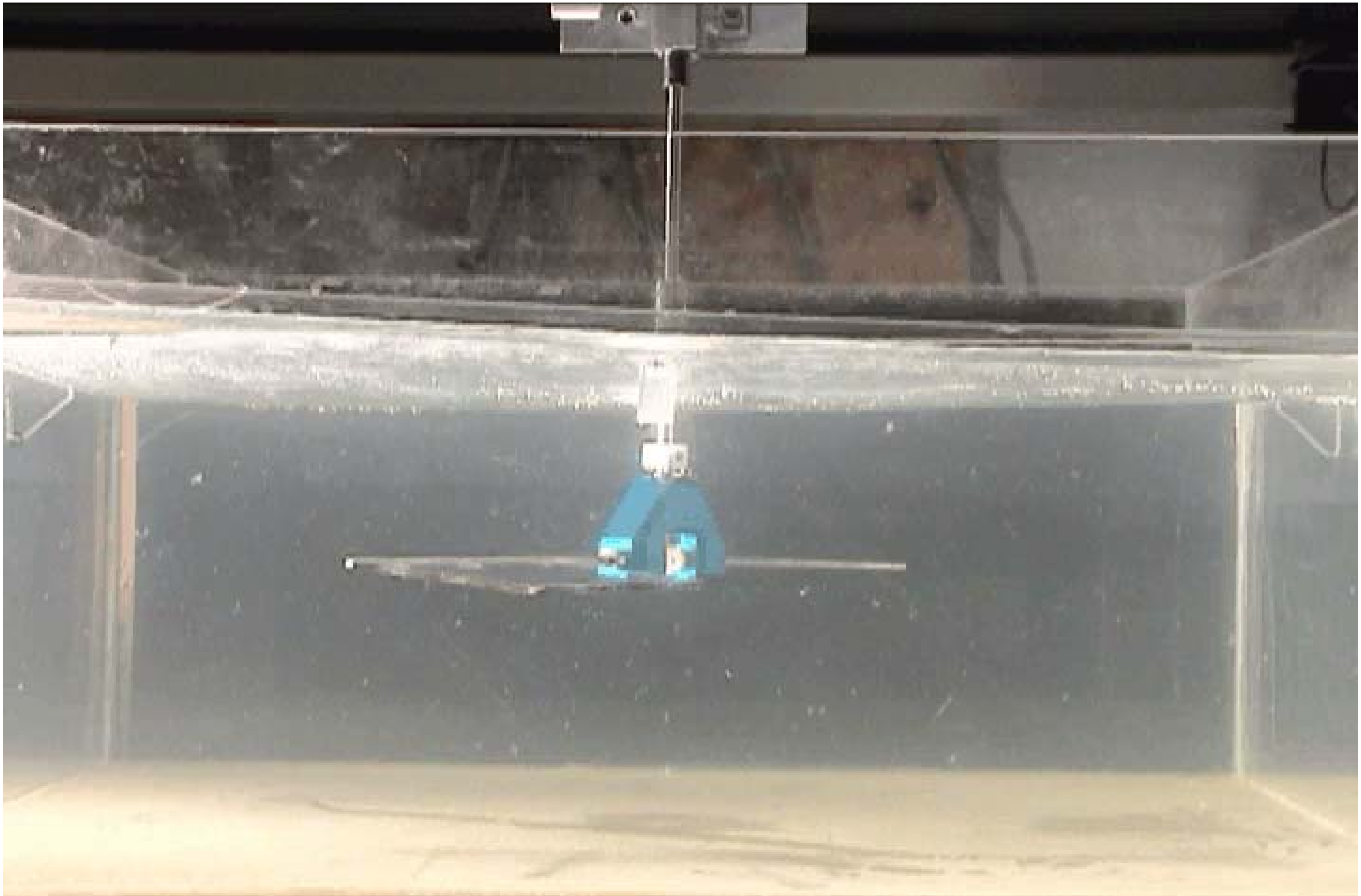
- Flapping amplitude: 2.7cm
- Wing chord: 8cm

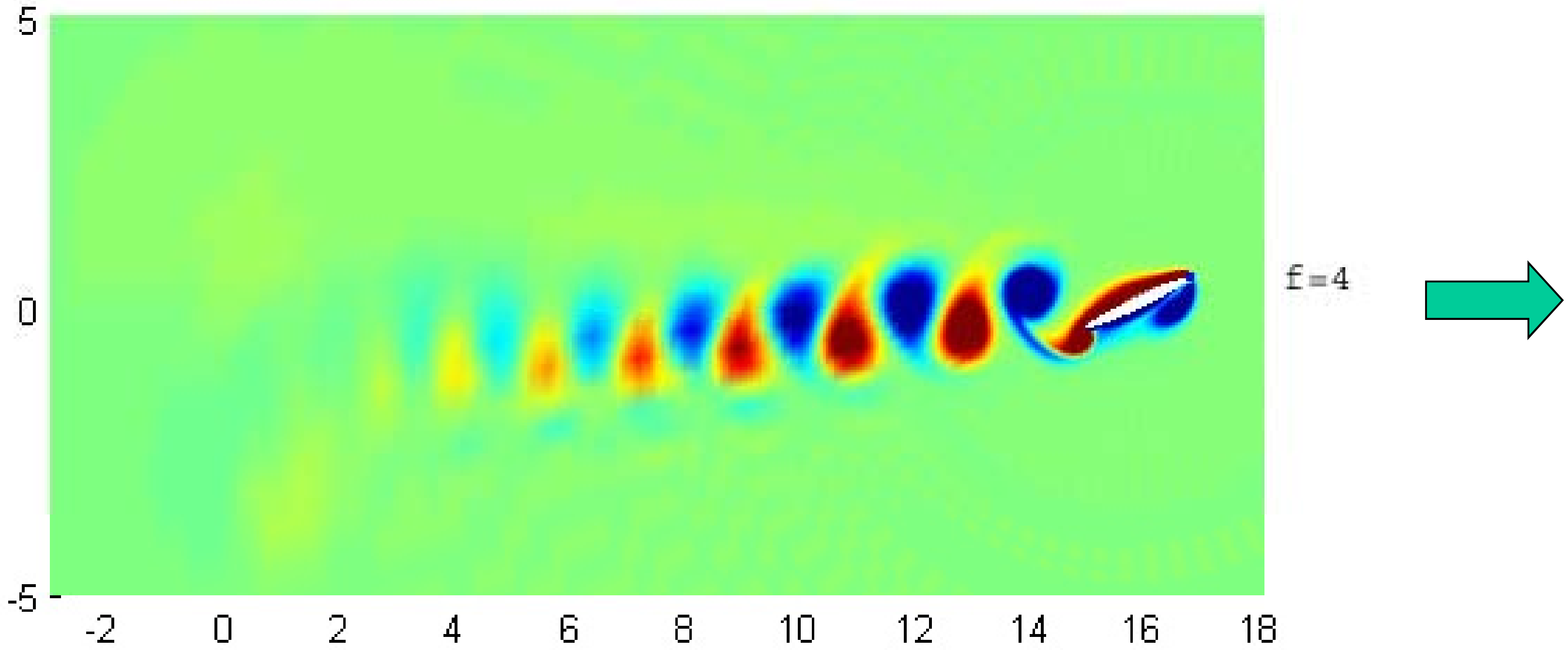
- Backward free flight is forbidden for low driving frequencies.
- Passive pitching can increase the speed for a given heaving motion.

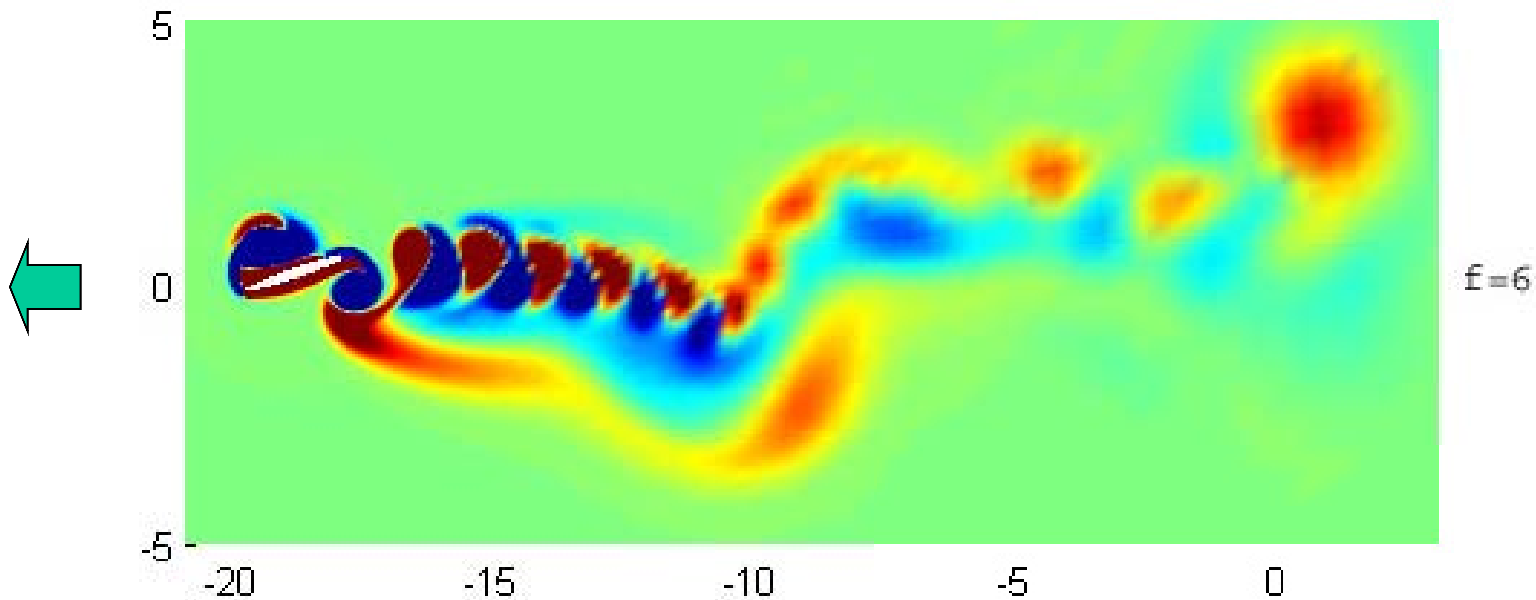
- Flexibility introduces forward/backward transitions.
- Forward free flight is forbidden above a threshold.



backward flapping flight:







<u>Spagnolie, Moret, Shelley and Zhang,</u> *Physics of Fluids, 2010*

Thanks.

Let’s talk.