Zu Chong-zhi Distinguished Lecture Math-Physics Series
Duke Kunshan University, July 09, 2020

Group Locomotion in Fluids

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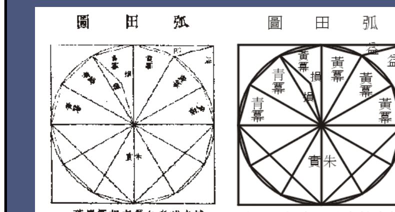
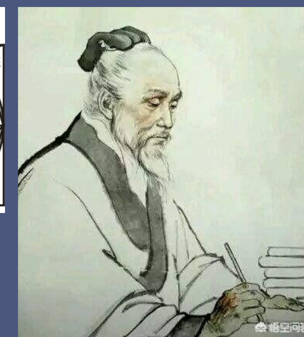
An astronomer, mathematician, politician, inventor, and writer
Zu Chong-zhi (祖冲之 429-500 AD) once a county governor of Kunshan





$\pi \approx 355/113$ as Zu's π ratio
$3.1415926 < \pi < 3.1415927$
holding a 800-year record

The lunar crater Tsu Chung-Chi

Asteroid 1964 VO1 was named 1888 Zu Chong-Zhi

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A fish school (shoaling or schooling)

[Image: Caine Delacy Stockesy.com]

3

Bird flocks (air is the "fluid")

To our eyes, these collections look messy but perhaps orderly since they don't seem to collide with each other.

(Images from the internet, yet to be credited)

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Schooling / flocking (of fish/birds)

= Social behavior + Physical interaction

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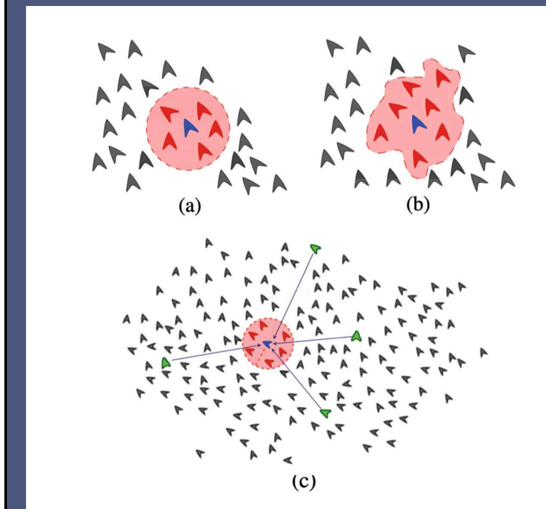

The "Vicsek Model" and its variations
PRL 1995

Left figure from:
Fig. 1 Sci. Rep.,
Zumaya et al. 2018

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Is the Vicsek model a
social model or physical model?

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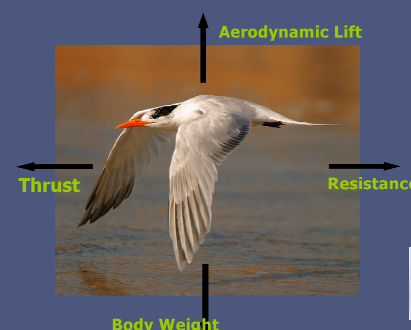
For a swimming fish or a flying bird, Re = $UL/\nu \sim 10^{2\text{-}5}$

And all forces $\sim U^2$



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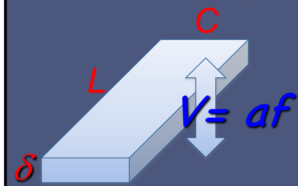
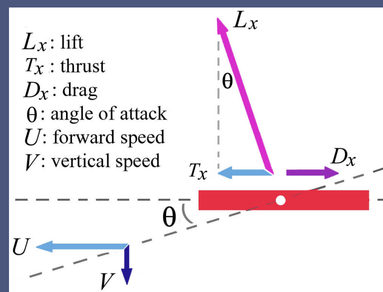
From a scaling or dimensional analysis:





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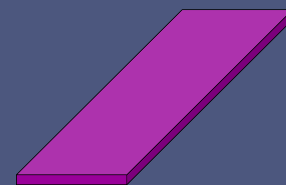
Question: Can a symmetric, rigid, flapped "wing" generate a lateral thrust and take a spontaneous forward flight?

The (physical) origin of flapping flight.



Vandenberghe, Zhang and Childress, Journal of Fluid Mechanics, 2004
Alben and Shelley, PNAS, 2005
Vandenberghe, Childress and Zhang, Physics of Fluids, 2006

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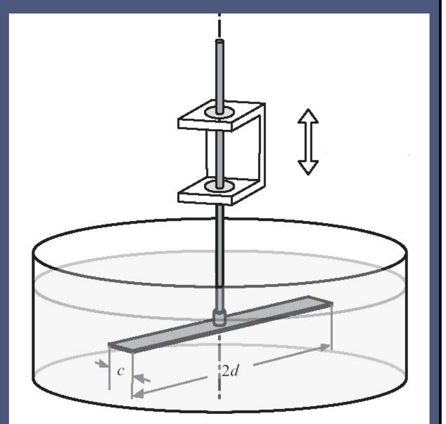
Experimental Setup: A **symmetric**, rigid wing is flapped vertically but it is **allowed to rotate freely** (AML 2004)

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

a: peak-to-peak flapping amplitude
f: flapping frequency



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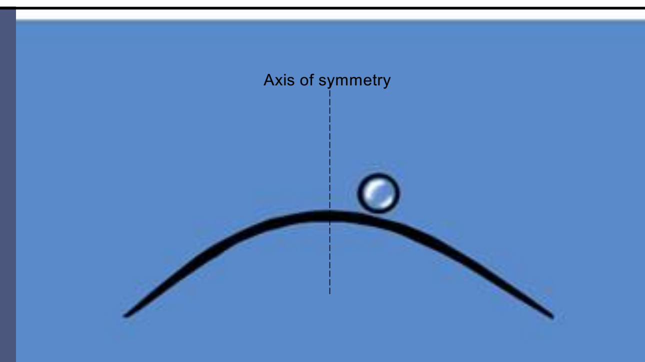

Spontaneous symmetry breaking bifurcation:
A "symmetric bird" would still fly "forward"...

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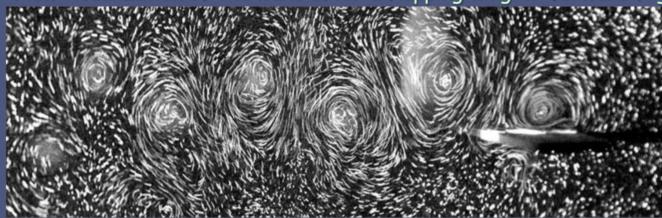
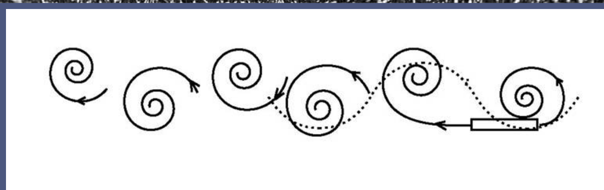
Flow visualization of the wake after a flapping wing in "forward flight"





Inverted von Kármán vortex street

Vandenberghe, Zhang and Childress, Journal of Fluid Mechanics, 2004

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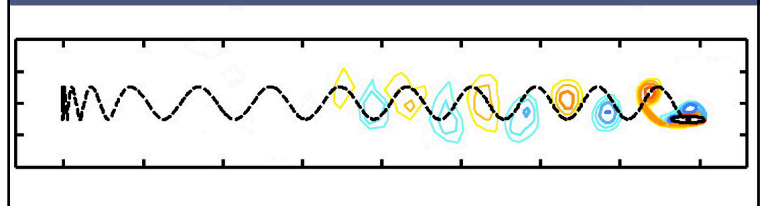

S. Alben and M. Shelley *PNAS*, 2005

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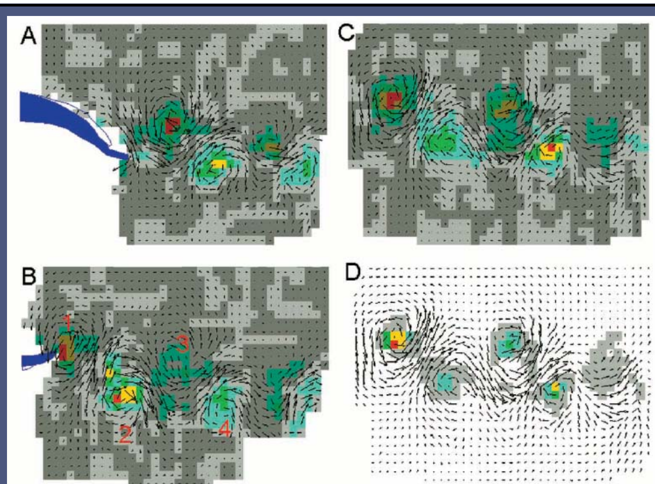

Muller et. al., FISH FOOT PRINTS: MORPHOLOGY AND ENERGETICS OF THE WAKE BEHIND A CONTINUOUSLY SWIMMING MULLET, Journal of Experimental Biology **200**, 2893–2906 (1997)

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What pattern(s) do they form?

What is the interaction with their neighbors?

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Daniel Weihs, Nature (1973)
A moving "diamond crystal" in fluids….

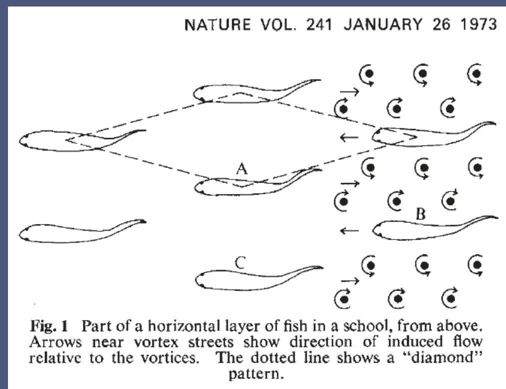
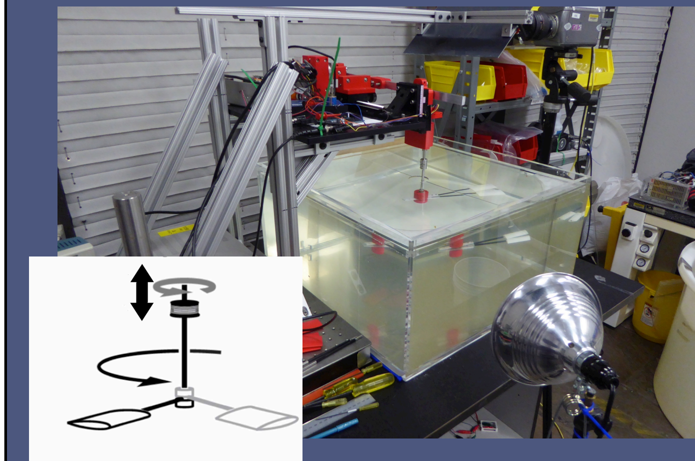
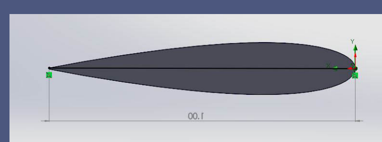

NATURE VOL. 241 JANUARY 26 1973

Fig. 1 Part of a horizontal layer of fish in a school, from above. Arrows near vortex streets show direction of induced flow relative to the vortices. The dotted line shows a "diamond" pattern.

Two tandem flapping wings, at NYU, 2014-2019

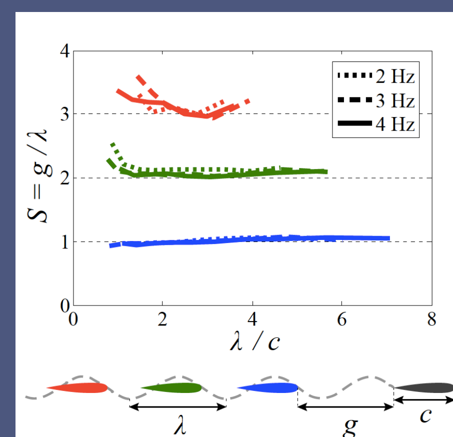


NACA0017
3D-printed PLA,
chord c = 4 cm, span s = 15 cm

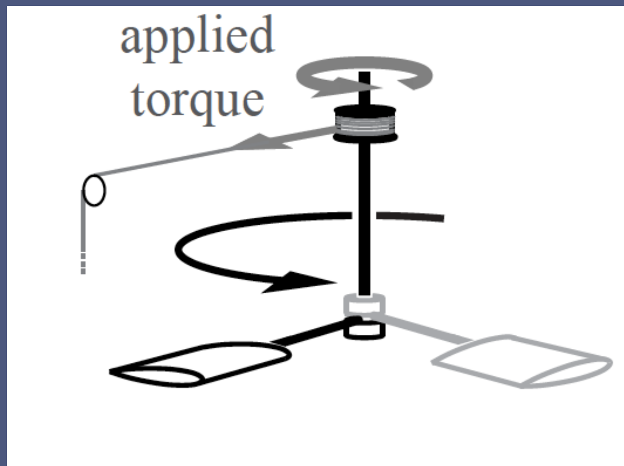


This wing would move only in one direction

We can change amplitude or amplitude to change wavelength λ



Romananarivo, Fang, Oza, Zhang, and Ristroph, Phys. Rev. Fluids 2016



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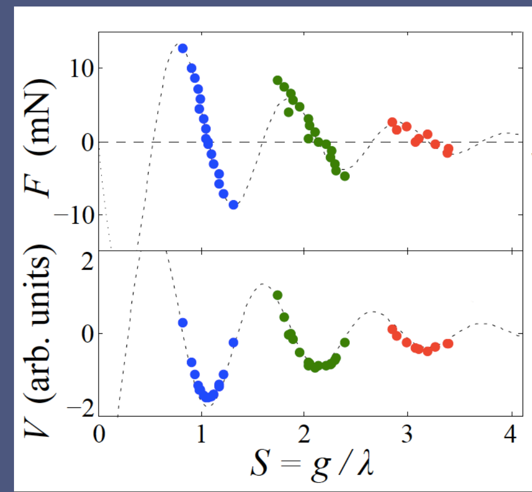
Romananarivo, Fang, Oza, Zhang, and Ristroph, Phys. Rev. Fluids 2016



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So far the flapping hydrofoils/airfoils have exactly the same "gaits" (i.e., same *freq* and *amplt*), and we have observed coherent motions and the pair takes stable locking positions.

What about two independent (different *f* and *a*) flapping foils that are placed in tandem?

How did we do it?

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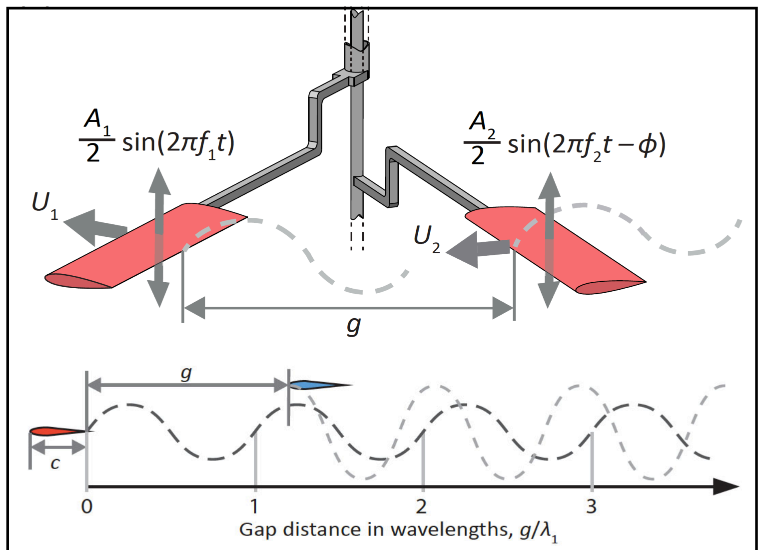

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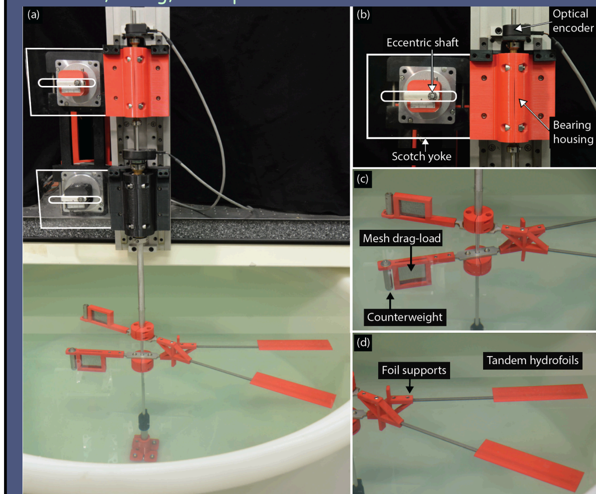
Newbolt, Zhang, Ristroph PNAS 2019



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Experimental demonstration

Supporting movie for
"Flow interactions between uncoordinated flapping swimmers give rise to group cohesion"

J. W. Newbolt, J. Zhang, & L. Ristroph

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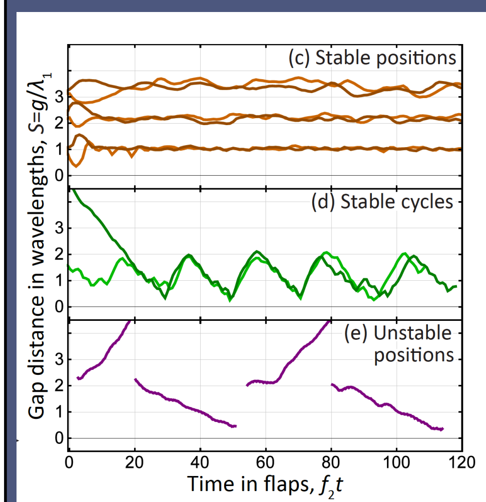

(c) multiple stable positions for $f_2/f_1 = 1$, $A_2/A_1 = 1$, and $\phi = 0$,

(d) stable cycles for $f_2/f_1 < 1$ but $A_2f_2/A_1f_1 > 1$,

(e) unstable for $f_2/f_1 > 1$ and $A_2f_2/A_1f_1 < 1$.

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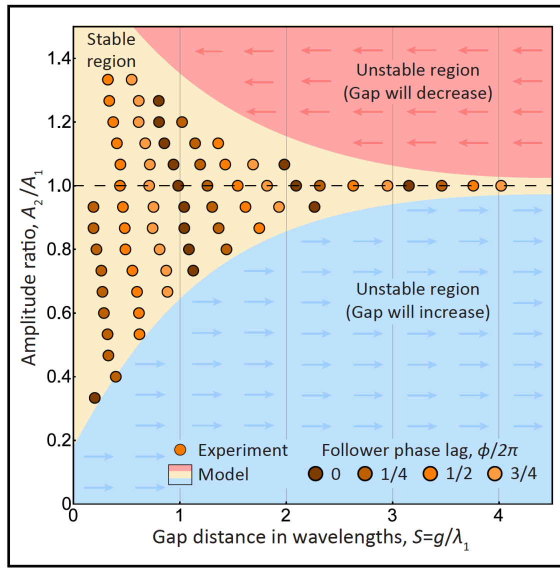

Same frequency, different amplitudes and different phases

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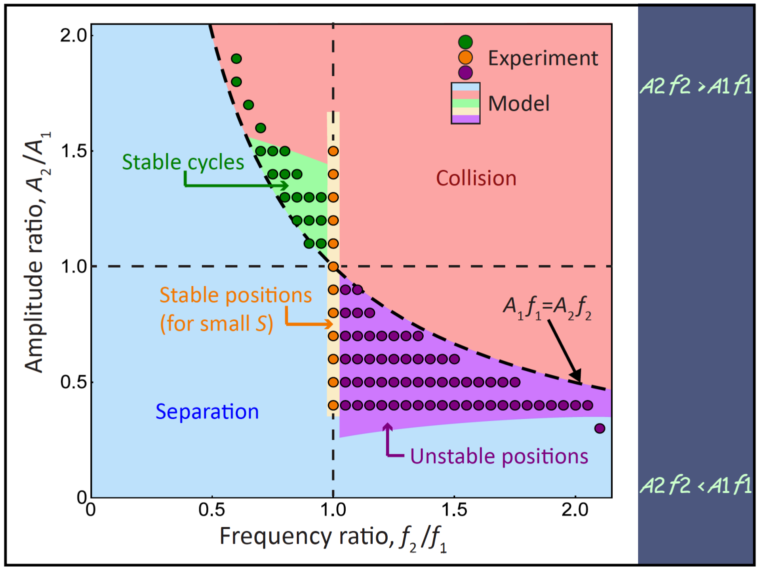


Stable states for tandem, flapping foils

Supporting movie for
"Flow interactions between uncoordinated flapping swimmers give rise to group cohesion"

J. W. Newbolt, J. Zhang, & L. Ristroph

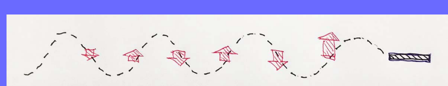
For fluid drag: $F_D = \frac{1}{2}\rho_f l^2 C_D U^2$

For thrust generated by a flapping wing (in quiescent fluid):

$$F_T = \frac{1}{2}\rho c s C_T V^2 = \frac{1}{2}\rho c s C_T (\pi A f)^2$$

Thrust generated in an unsteady flow:

$$F_T = \frac{1}{2}\rho c s C_T \pi^2 (V_{wing} - v_{flow})^2$$

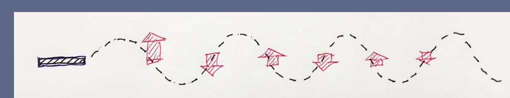


The periodic wake after a flapping wing (#1), seen by a follower (#2):

$$v_{flow} = \pi A_1 f_1 e^{-\Delta t/\tau}\cos[2\pi f(t-\Delta t)]$$

The core of the wake-interacting model (tandem formation):

$$F_T = \frac{1}{2}\rho c s C_T v^2 = \frac{1}{2}\rho c s C_T (\pi A f)^2 \Rightarrow \frac{1}{2}\rho c s C_T \pi^2 (v_2 - v_1')^2$$

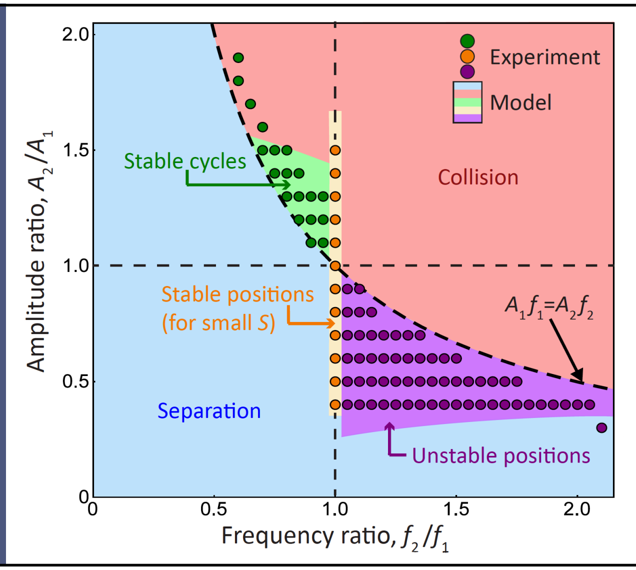


$$F_{T,2} = \frac{1}{2}\rho c s C_T \pi^2 \left[A_2 f_2 \cos(2\pi f_2 t - \phi) - A_1 f_1 e^{-\Delta t/\tau}\cos(2\pi f_1 (t - \Delta t))\right]^2.$$

The average thrust over a flapping period, $\langle F_{T,2}\rangle \equiv \frac{1}{T_2}\int_t^{t+T_2} F_{T,2} dt$ may be approximated if we assume that Δt is constant over a flapping period and $f_2 \approx f_1$:

$$\langle F_{T,2}\rangle \approx \frac{\rho c s C_T \pi^2}{2}\left[\frac{1}{2}(A_2 f_2)^2 + \frac{1}{2}(A_1 f_1 e^{-\Delta t/\tau})^2 - A_2 f_2 A_1 f_1 e^{-\Delta t/\tau}\cos\{2\pi f_2 t - \phi - 2\pi f_1 (t - \Delta t)\}\right].$$

"Flow interactions between uncoordinated flapping swimmers give rise to group cohesion", **116**, 2419, PNAS 2019
by J. Newbolt, J. Zhang, L. Ristroph



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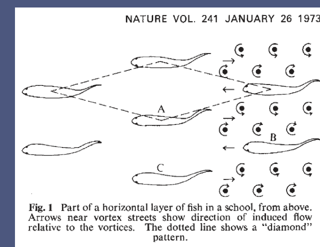
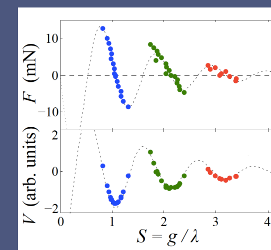
Can we ever see a fish school or bird flock that resembles a crystal (in the Weihs' model)?





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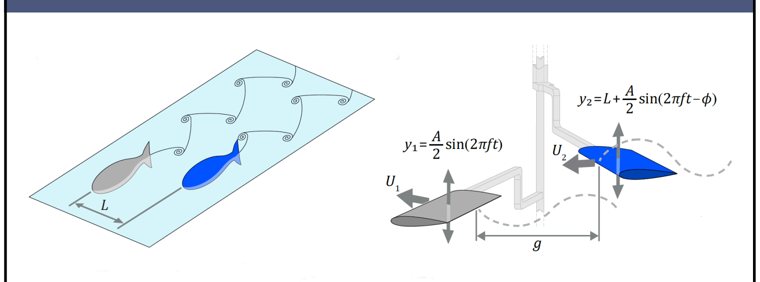
NOW, we further relax on the tandem conditions, studying lateral interactions between flapping wings.

Joel Newbolt, Leif Ristroph, JZ 2020
Submitted…



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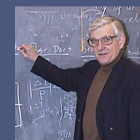
Collaborators:


Steve Childress


N. Vandenberghe

Flight bifurcation (experiments)


M. Shelley


S. Alben

Flight bifurcation (DNS)


S. Ramananarivo


J. Newbolt


L. Ristroph

Schooling of flapping flyers / swimmers (experiments)

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Messages….reflections….

Physics/math models provide a solid base for biological locomotion systems (well, nobody escapes physics laws). The dynamics, kinematics and thus behaviors can be better understood by means of "simple" biomimetic experiments, theory, and simulations.

"Social behaviors" should not act against physical interactions.

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Thank you

http://physics.nyu.edu/jz11/

Email: nycdot@gmail.com

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