Wake-structure interactions: analysis and experiments

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Project Statement

The objective of the research project is two-fold:

- Execute wake experiments on vertically flowing soap films and validate the analytical calculations based on experimental feedback
- Compare the dynamic effects of vortex-dominated wakes induced by a wake shedding bluff body on the wake-shedding bluff body, with the experimental results

Soap film experiments

Flowing soap films are used to study 2D turbulence, cylinder wakes, and wakes shed by foils.

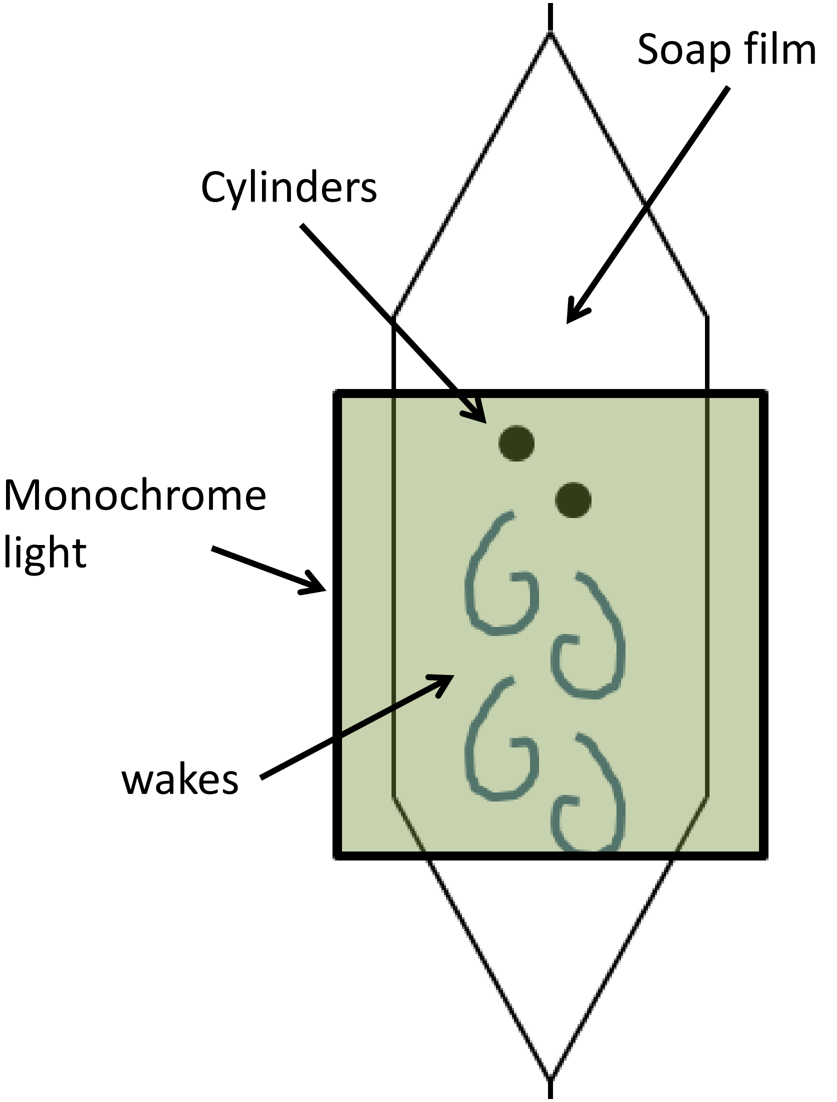
Soap film characteristics

- Has uniform velocity profile and constant thickness
- Behaves as 2D incompressible fluid
- Flow structures are viewed using a monochrome light source

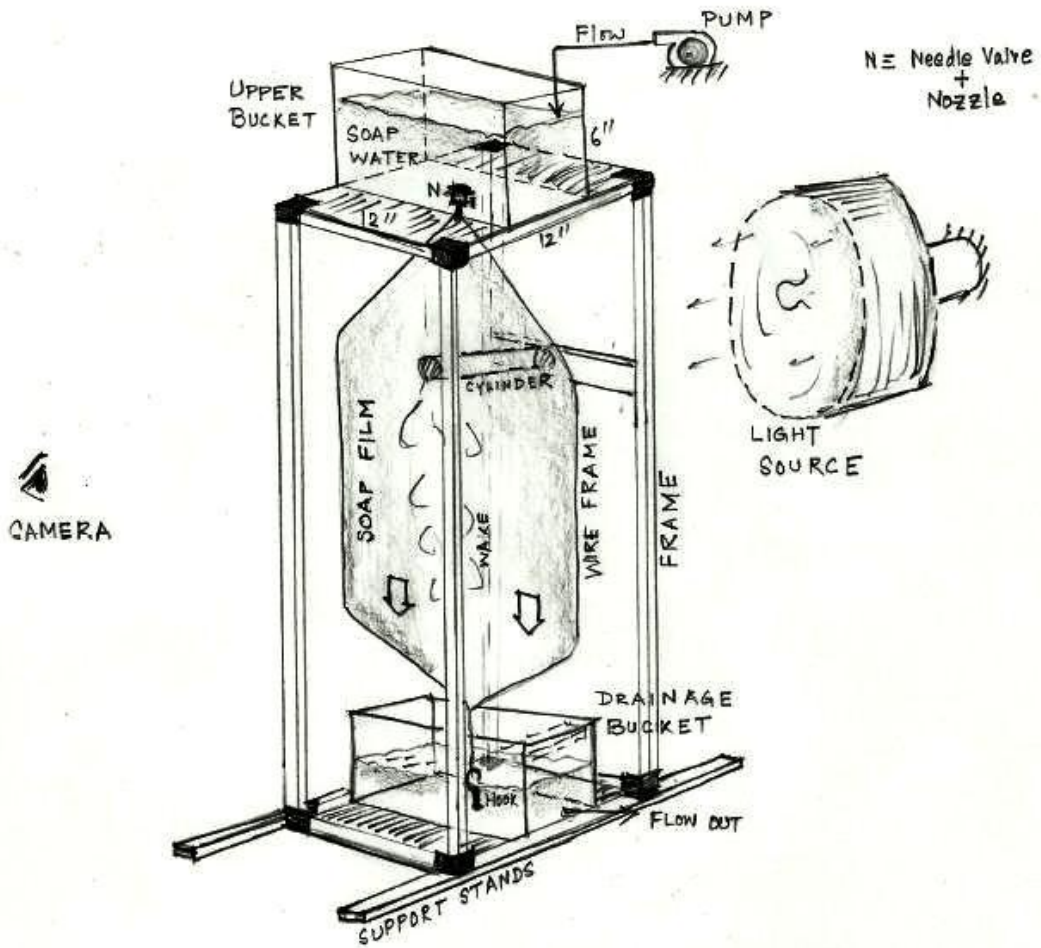
Targets for the experiments

The main objectives of the soap-film experiments are:

- Generation of wakes through free oscillation of the body and staggered cylinders
- 2P mode generation is the target (this would be a valuable addition to the existing literature)
- 2P wakes serve as the feedback framework (using model predictions) to validate and confirm the structural response formulation



Our Setup



FLOW
PUMP
N = Needle Valve + Nozzle
UPPER BUCKET
SOAP WATER
6"
12"
12"
CYLINDER
SOAP FILM
WAKE
WIRE FRAME
FRAME
LIGHT SOURCE
CAMERA
DRAINAGE BUCKET
HOOK
FLOW OUT
SUPPORT STANDS

Setup Difficulties

- Air drafts and other disturbances made the film unstable
  - So we shortened the test section from 6 ft to 3 ft
- Our monochrome light source was very weak (only 16 W)
  - This made interference fringes difficult to see
  - We are purchasing a 90 W sodium lamp to increase contrast

Experimental results

Two stationary cylinders were placed in the flow to generate 2P wakes

Monochromatic light allows for visualization of interference patterns

- The speed of flow structures changes the thickness of the film

Our film was too thick

- Due to shortening of the test section

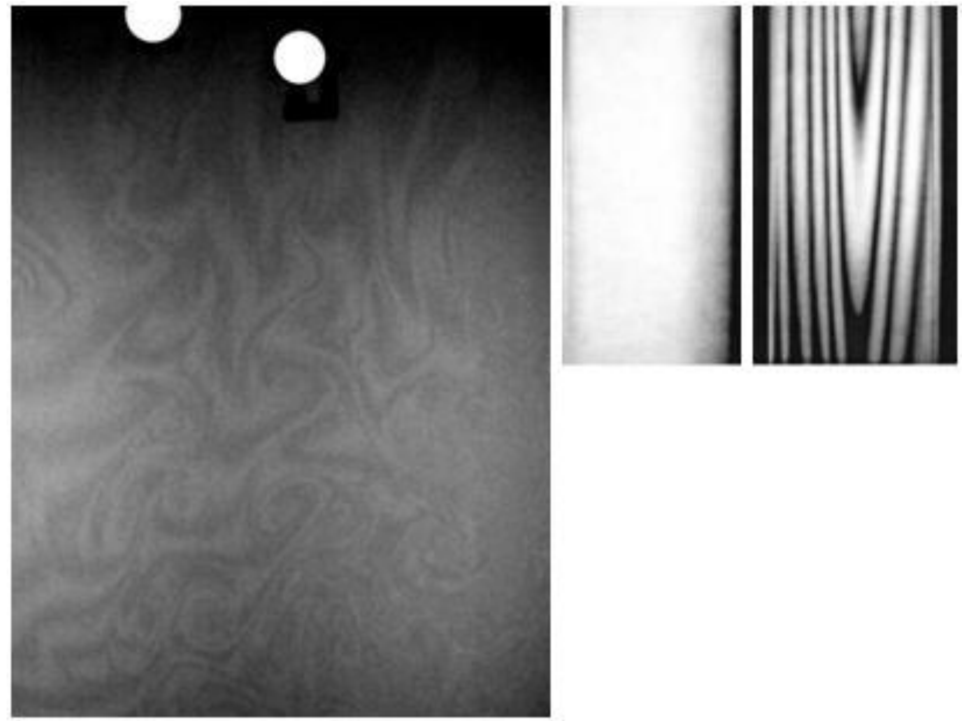
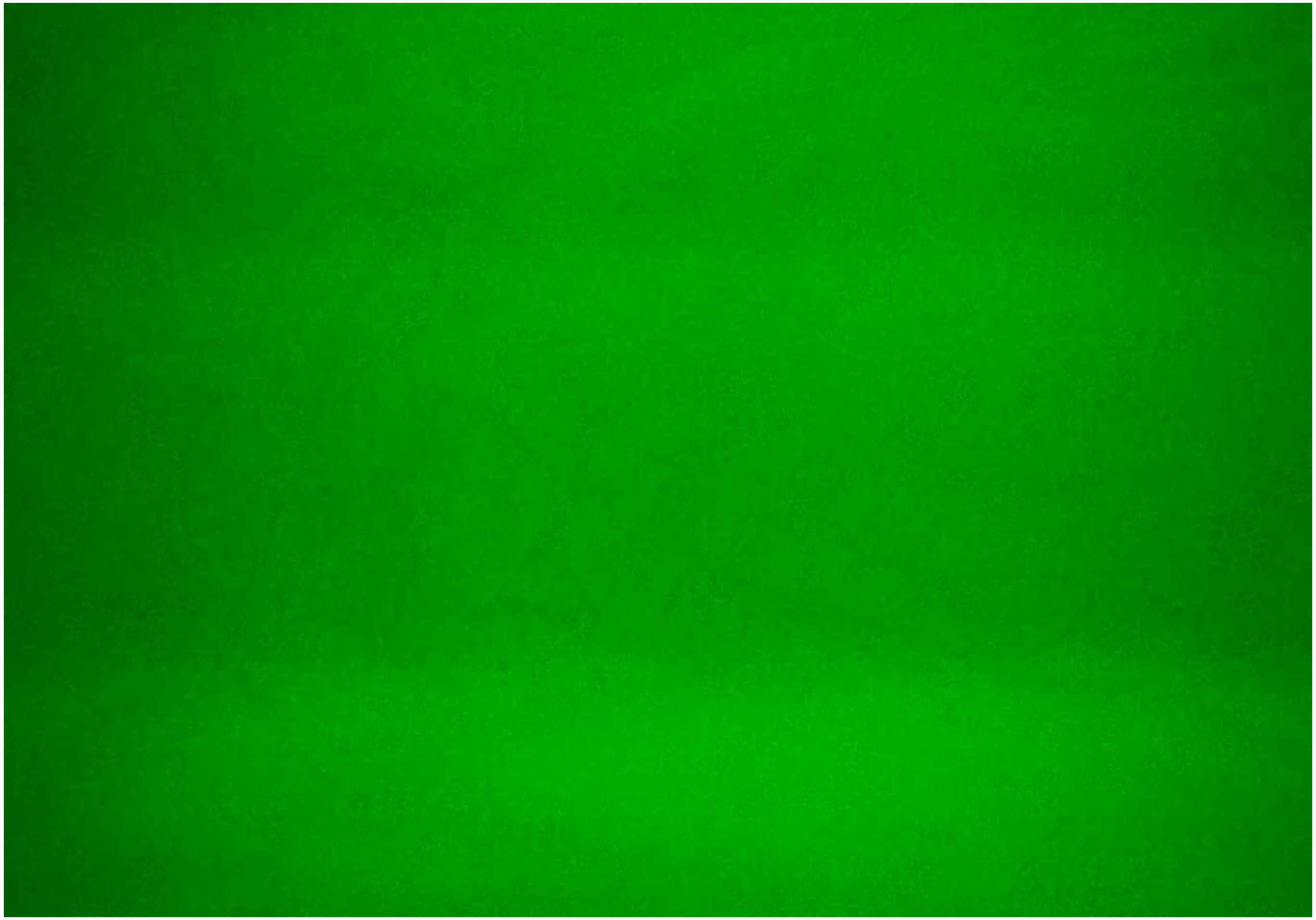


Figure: Wake visualizations. White circles highlight cylinder locations. Middle: Example of correct film thickness, Right: A film that is too thick (All images from Rutgers et al 2001).

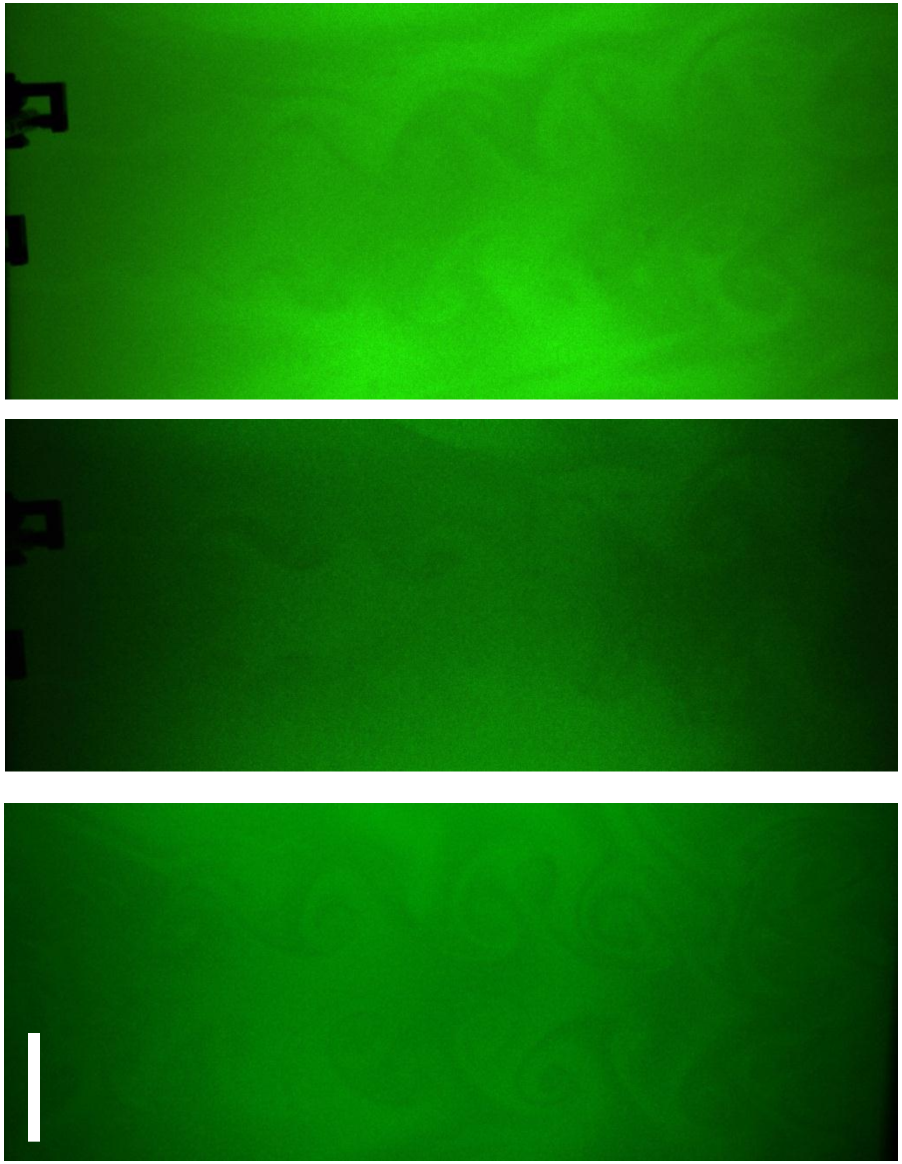
Experiment Results



Experimental results

The cylinders were placed one-half period length apart to generate symmetric 2P wakes

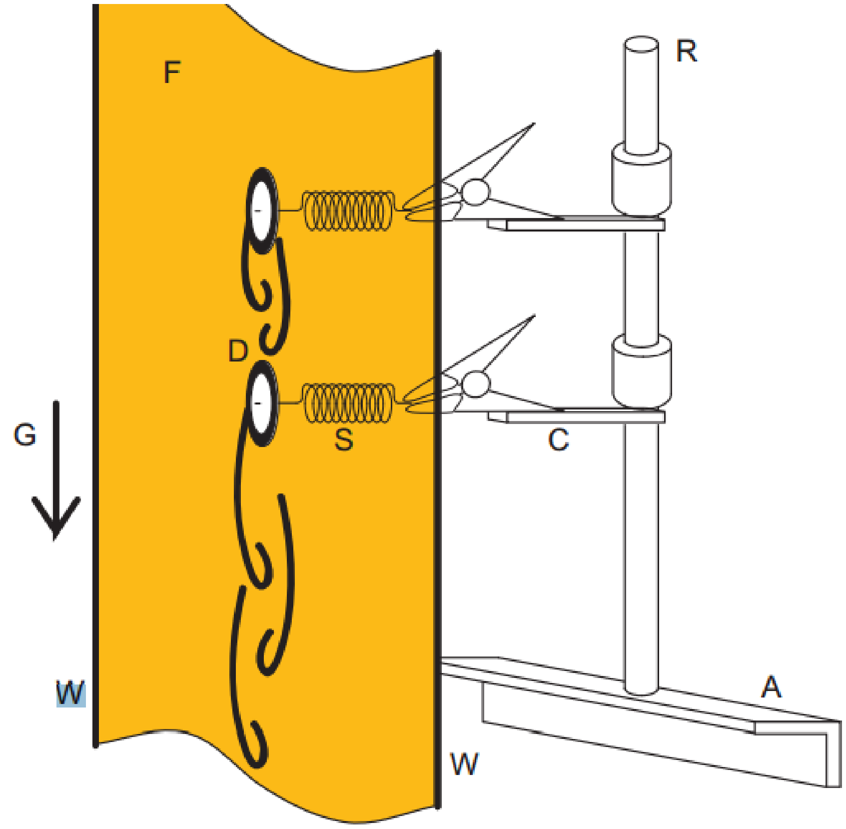
We are only able to visualize 3-4 periods and do not know the velocity of the film so comparison with theory is not possible at this time



Scale: 20 mm

Future Experimental Work

- A more powerful monochrome light will make visualizing fluid structures much easier
- Measure the flow velocity using LDA
- Use freely oscillating Styrofoam cylinders as in (Hobbs & Hu 2011)



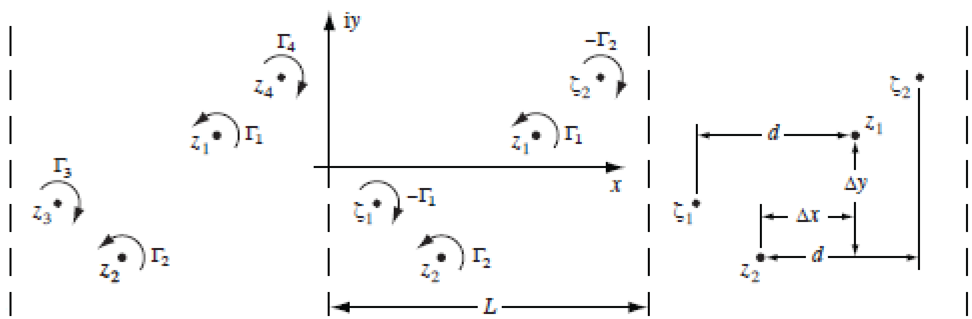
Hobbs & Hu, J. Fluids & Struct. 2011

Point vortex model of complex vortex wakes

- Point vortex model (von Kármán, Rubach 1912) exists for the well-known 2S mode wake (von Kármán vortex street).
- For 2P mode wakes (with 2 counter-rotating vortex pairs per cycle), it has been possible to to do a point vortex approximation and after some symmetry constraints, the problem can be reduced to the Hamiltonian form. This is one of the most common wake forms after the 2S mode.

$$\mathbb{H}(\Delta x, \Delta y) = -\frac{1}{2\pi}\left[\ln\left\{\frac{\sin^2(\pi\,\Delta x/L) + \sinh^2(\pi\,\Delta y/L)}{\cos^2(\pi\Delta x/L) + \sinh^2[\pi(\mathbb{P} + (1-2\gamma)\Delta y/L]}\right\}\right.$$

$$\left. - \frac{\gamma}{1-\gamma}\ln\left\{\cosh\left[\pi\left(\mathbb{P} + 2\left(1-\gamma\right)\Delta y/L\right)\right]\right\} - \frac{1-\gamma}{\gamma}\ln\left\{\cosh\left[\pi\left(\mathbb{P} - 2\,\gamma\,\Delta y/L\right)\right]\right\}\right]$$



Canonical EOMS

$$\frac{2}{\mathbb{S}}\frac{\mathrm{d}(\Delta x)}{\mathrm{d}t} = \frac{\partial \mathbb{H}}{\partial(\Delta y)}$$

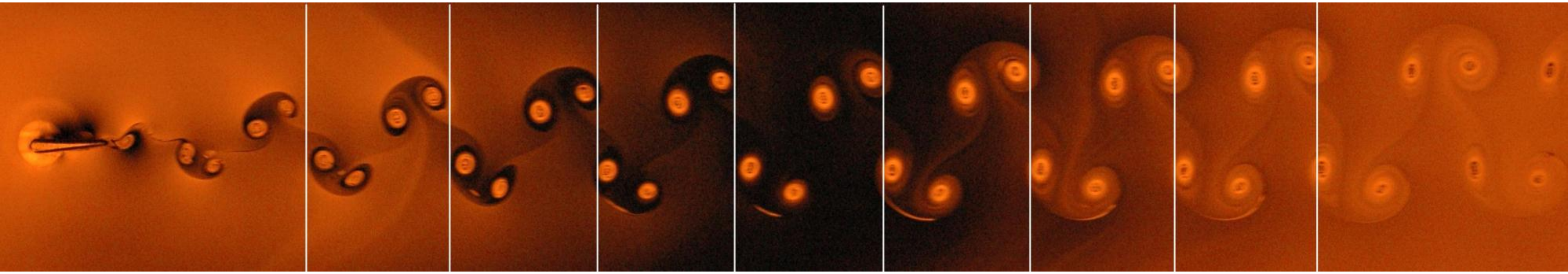
$$\frac{2}{\mathbb{S}}\frac{\mathrm{d}(\Delta y)}{\mathrm{d}t} = -\frac{\partial \mathbb{H}}{\partial(\Delta x)}$$

Feedback (or, main take-aways) from the point vortex model for our project

- The model provides a good representation of the dynamics in the mid-wake region.

- It is possible to predict the strengths of the individual vortices as well as their evolving dynamics.

- The model prediction of a vortex spatial evolution over time fits well with existing experiments



Andersen, Bohr, and Schnipper (Theoretical & Computational Fluid Dynamics, 2011).

Calculation of the wake-induced lift force

- **Approach 1:** Conservation of linear momentum on a control volume (conceptually similar to von Kármán's analysis for the 2S structure using momentum conservation [3], [4])

- **Approach 2:** Combination of the integrable point vortex model (introduced in this thesis) for mid-wake with the unsteady point vortex model [5] involving the vortex shedding process in the near-body region of the wake

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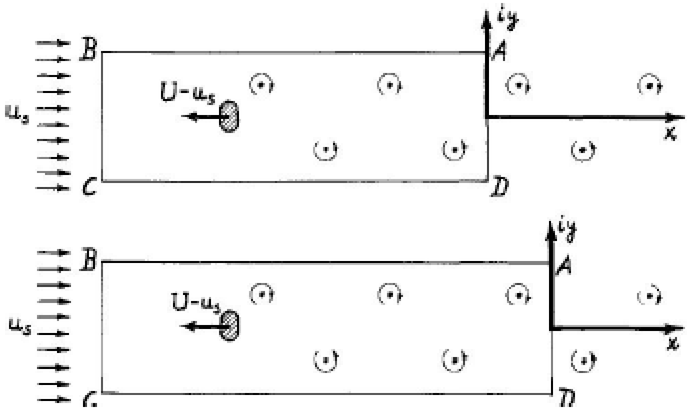
[3] von Kármán and Rubach (Physicalische Zeitschrift, 1912)
[4] Sallet (J. Aeronautics, 1973)
[5] Michelin and Llewellyn Smith (Theoretical & Computational Fluid Dynamics, 2009)

Approach 1: Linear momentum conservation - Tracking von Kármán's solution

Following calculations by D. W. Sallet (J. Aeronautics, 1973)

- Cylinder moves with a velocity U to the left
- Coordinate system moves with a steady velocity u_s to the left (same as the vortex system; thus the vortex system is stationary and the cylinder has a velocity $U - u_s$ to the left, w.r.t. to the coordinate system)



Sallet (J. Aeronautics, 1973)

- Linear momentum conservation for a control volume (includes the shedding body) over a time increment during which a new pair of vortices are shed into the fluid, leads to the formulation for the wake-induced dynamic effects on the structure.
- $\boxed{L = \frac{1}{4}\rho\Gamma\left[U - 3u_s\right]}$

Approach 1: Linear momentum conservation - Tracking von Kármán's solution

Application of von Kármán's method to the 2P wake

- For **relative equilibrium configurations** , the application of von Kármán's momentum approach will be quite straight-forward.

  The main points of distinction would be:

  - Velocity field owing to the vortex street is different, and so is the translational velocity of the vortex system
  - Different spatial symmetry

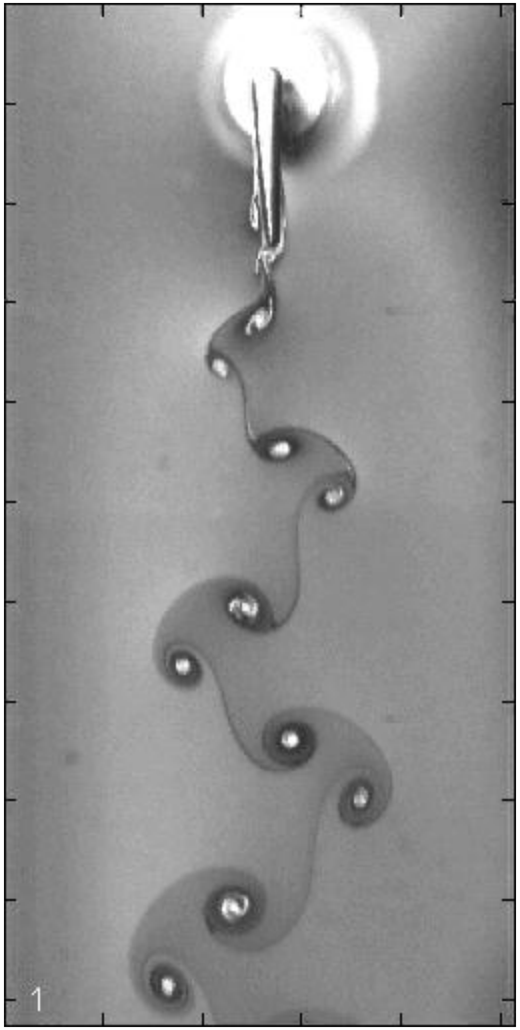
- For **time-evolving vortex patterns**, the computation of the evolved locations of the individual vortices (non-equilibirum being the cause of the complexity) over a time increment and using the information for the momentum conservation analysis would be the primary challenge.

In Summary

We designed and built a flowing soap film apparatus to visualize wake structures shed from staggered stationary cylinders

A point vortex model is reviewed for future comparison with experiments

There were some difficulties with experiments that will need to be fixed (light source, film stability)



Andersen, Bohr, and Schnipper (Theoretical & Computational Fluid Dynamics, 2011).

Questions?