Time domain analysis of vortex-induced vibrations (VIV)

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Introduction

- About me:
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  - PhD 2012-2016
  - Topic: VIV
  - Supervisors:
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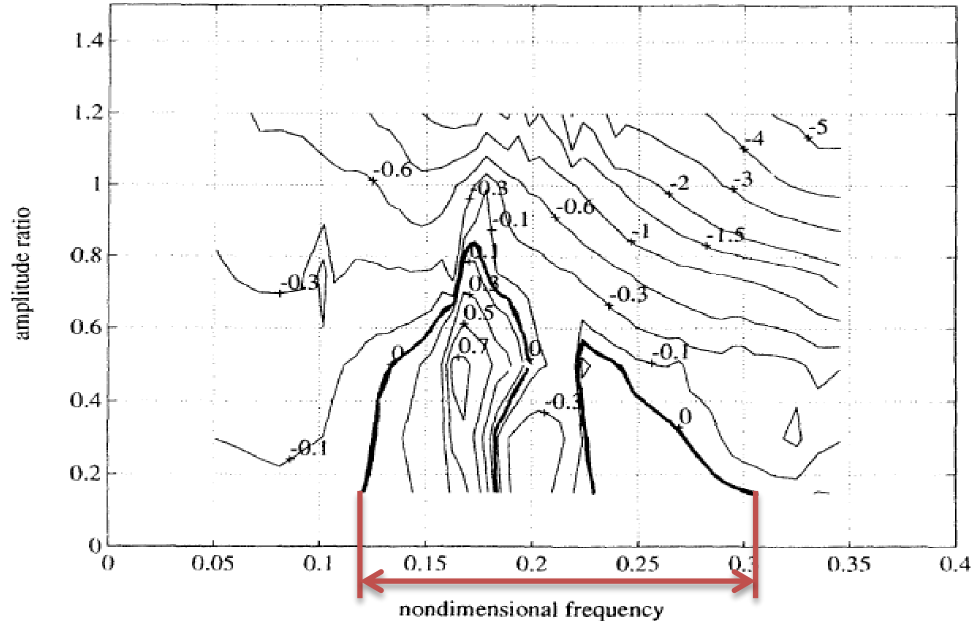
Motivation

- Traditional VIV analysis tools operate in frequency domain.
- Freq. domain limitations:
  - Linear structure
  - Stationary conditions (e.g. constant current velocity)

- A time domain formulation would allow for:
  - Nonlinear effects (tension variations, soil contact, etc.)
  - Time varying currents
  - Interaction with other loads (e.g. internal flow)

VIV fundamentals

- For a fixed cylider, $f_s = St\frac{U}{D}$, where $\mathrm{St} \approx 0.2$
- Forced vibration experiment, Gopalkrishnan (1993):



- For a vibrating cylinder, the vortex shedding synchronizes with the cylinder motion over a range of frequencies

Synchronization

- Inspiration:
  - Fireflies!

- Gather in very large groups and flash in unison

- Researchers have studied/modeled their synchronization

Fireflies

- Hanson (1978) did experiments with periodically flashing light. How does the firefly synchronize?
  - ω_0 : Firefly natural frequency
  - ω_e : Frequency of flashing light

- Findings:
  - For a range of ω_e *close to* ω_0 the firefly synchronizes
  - If ω_e is too far from ω_0, the firefly does not keep up.

- Note similarities with vortex shedding!

Firefly modeling

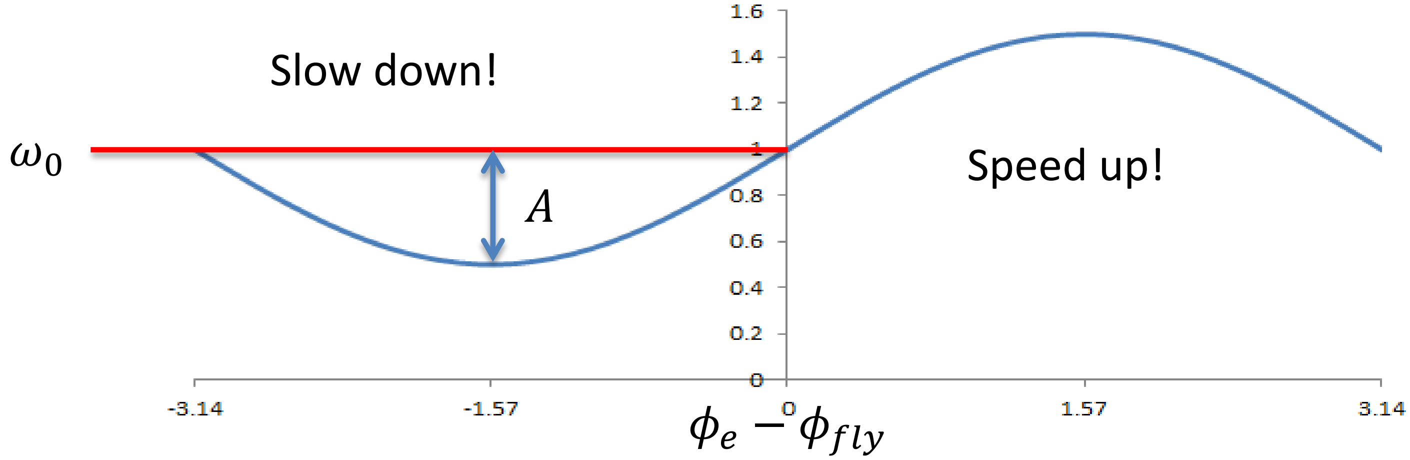
ϕ_e: Phase of flashing light. Flash when $\phi_e = 0$

$\frac{d\phi_e}{dt} = \omega_e$: Frequency of flashing light

ϕ_{fly}: Phase of firefly

- Model proposed by Ermentrout and Rinzel (1984):

$$\frac{d\phi_{fly}}{dt} = \omega_0 + A\sin\left(\phi_e - \phi_{fly}\right)$$



Back to VIV

- Assume the cross-flow excitation force can be expressed as $\frac{1}{2}\rho D U^2 C_v \cos\phi_{exc}$
  - ϕ_{exc}: Phase of the cross-flow excitation force
  - $\phi_{\dot{y}}$: Phase of cylinder cross-flow velocity

- Synchronization model:

$$\frac{d\phi_{exc}}{dt} = H(\underbrace{\phi_{\dot{y}} - \phi_{exc}}_{\text{Phase difference between velocity and force}})$$

(Similar to Ermentrout and Rinzel)

Phase difference between velocity and force

- How to find H?

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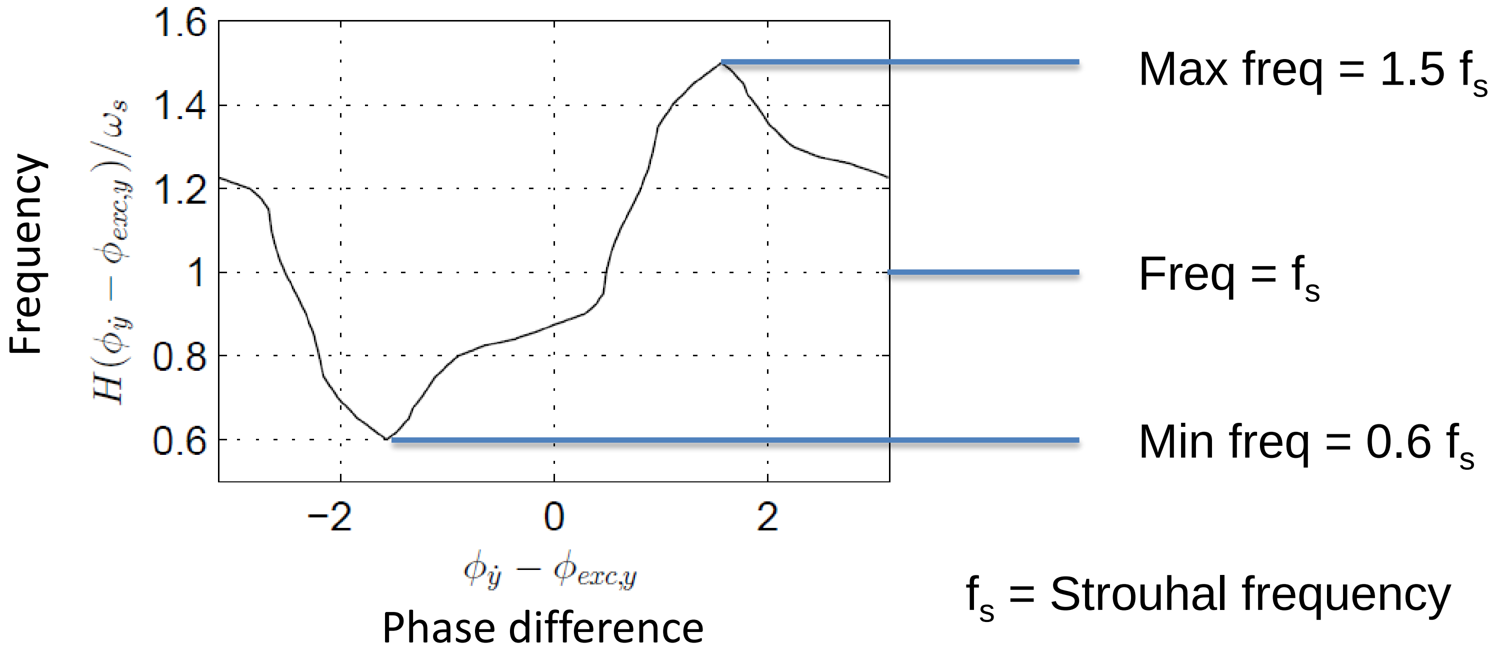
Finding H, the synchronization function

- In the range of synchronization, assume

$$C_{exc}(\omega) = C_{exc,max} \cos\big(\theta(\omega)\big)$$

- Plot ω versus θ based on VIVANA's C_{exc}:



f_s = Strouhal frequency

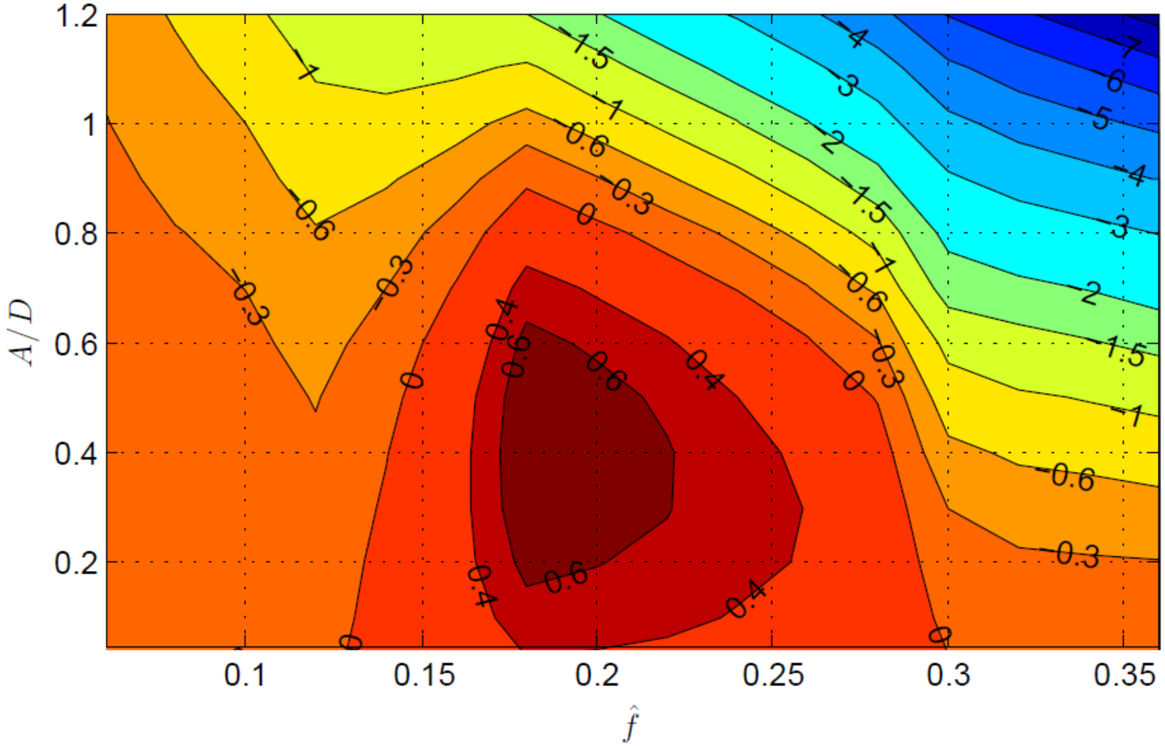
Cross-flow hydrodynamic force model

$$F_{fluid,y} = \underbrace{\frac{1}{2}\rho D C_v U^2 \cos\phi_{exc,y}}_{\text{excitation}} \underbrace{-\frac{1}{2}\rho D C_{y1} U \dot{y} - \frac{1}{2}\rho A_y C_{y2} |\dot{y}| \dot{y}}_{\text{damping}} \underbrace{-\frac{\rho \pi D^2}{4} C_{ay} \ddot{y}}_{\text{added mass}}$$

1. Excitation with synchronization
2. Hydrodynamic damping
3. Added mass, $C_{ay} = 1$

Results

- Does the model provide a realistic description of the energy transfer between fluid and structure?
- Simulated forced vibration experiment:



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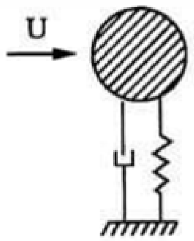
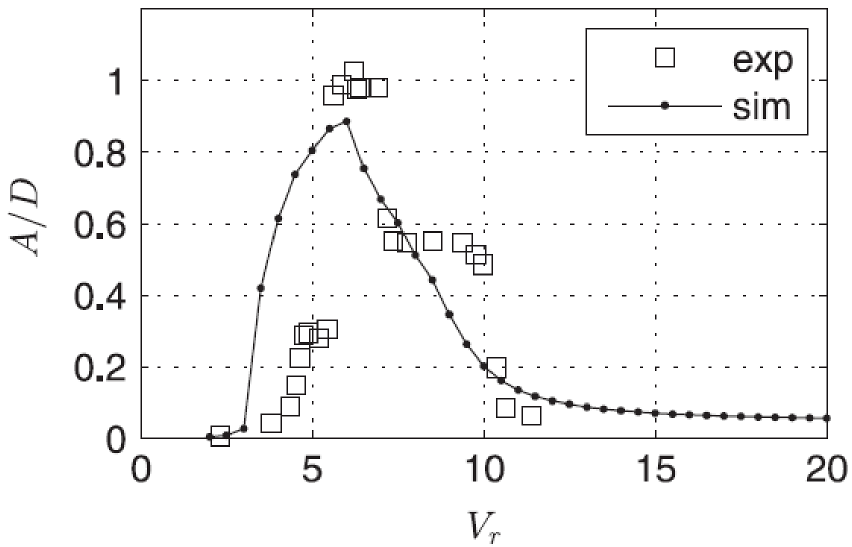
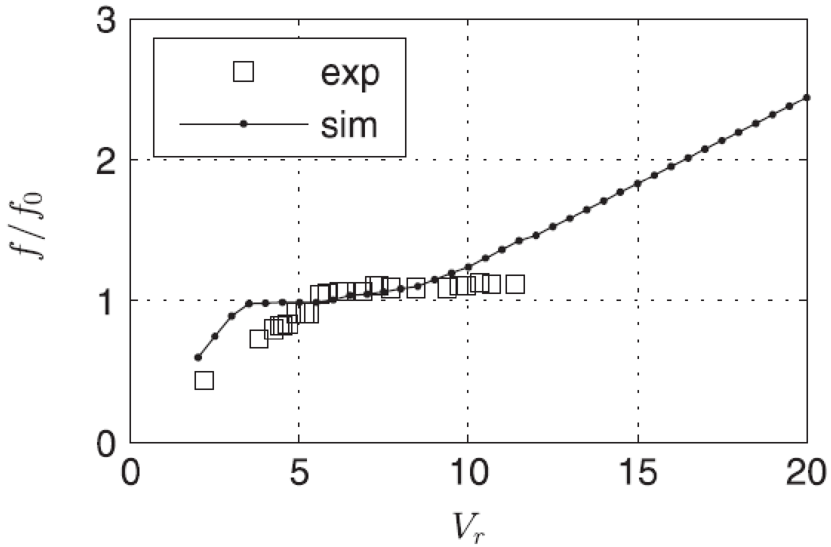
Results



- Can the model predict the amplitudes and frequencies seen in classical 1-DOF experiments?

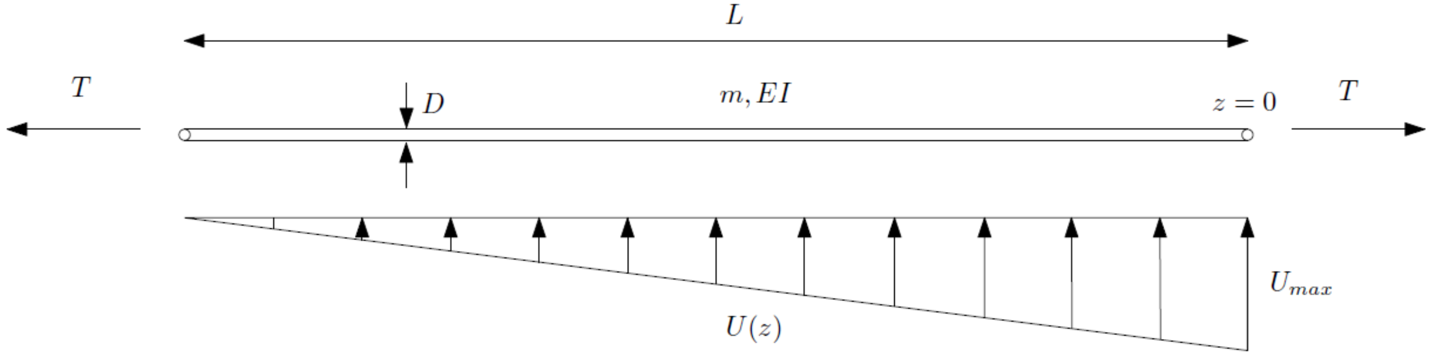




Simulation compared to experiment (Govardhan & Williamson, 2000)

Results

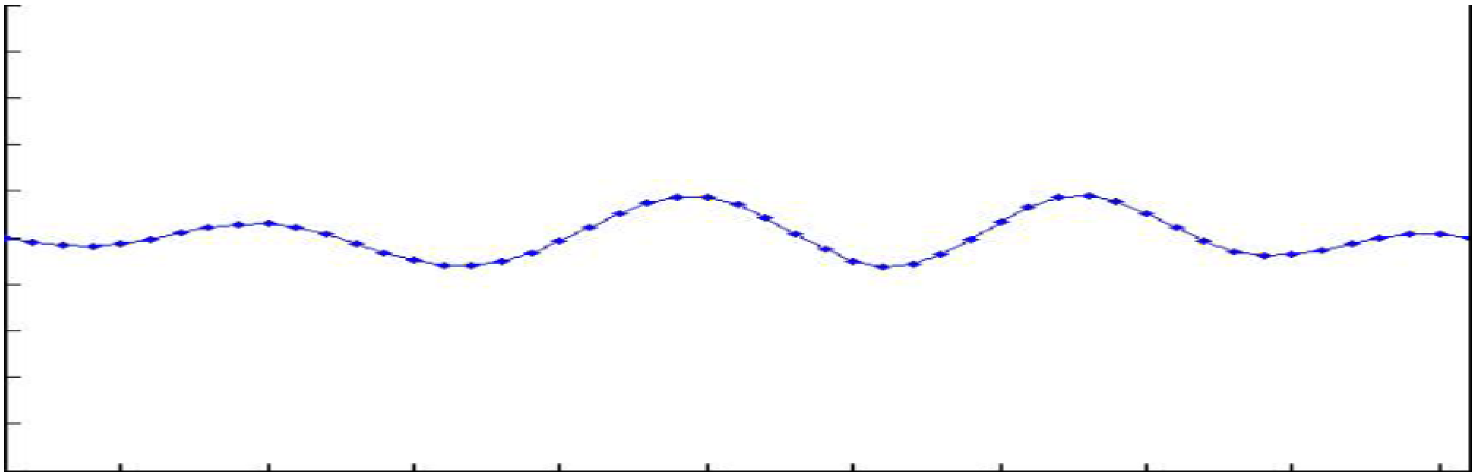
Elastic cylinder in shear flow (NDP High Mode VIV tests)



- Linear beam FE model
- Hydrodynamic force calculated at every node
- Time integration using Newmark-β

Results

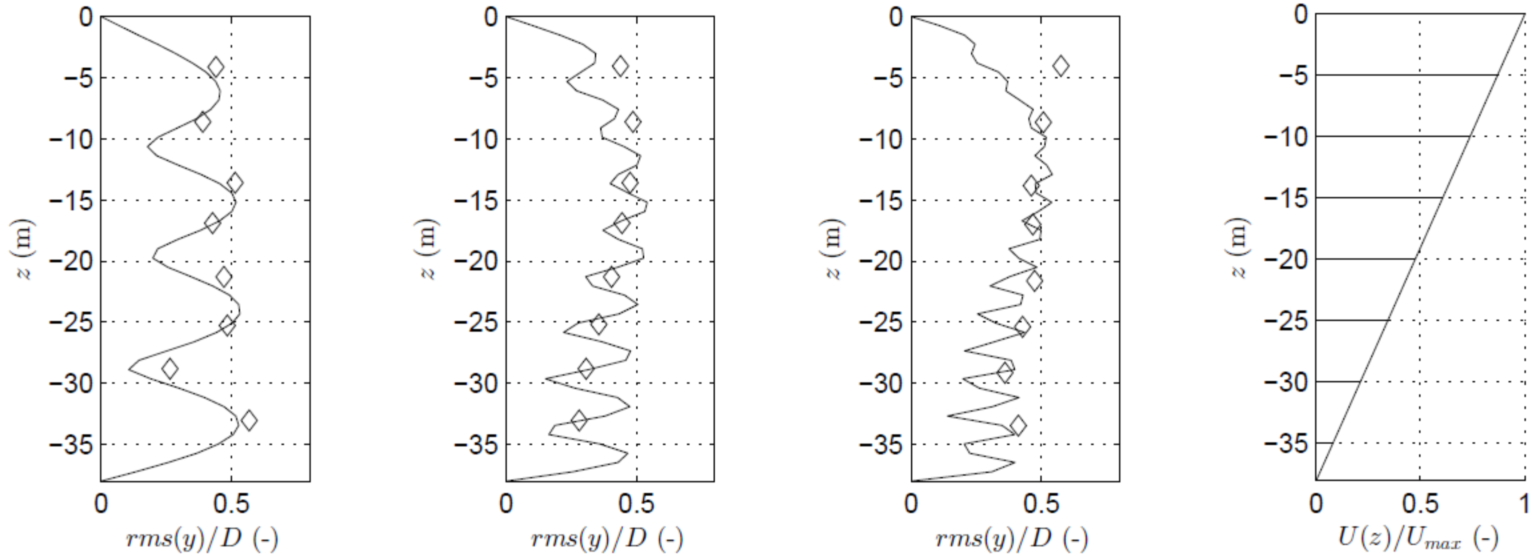
Elastic cylinder in shear flow



Results

Elastic cylinder in shear flow

Cross-flow response compared to experiment:

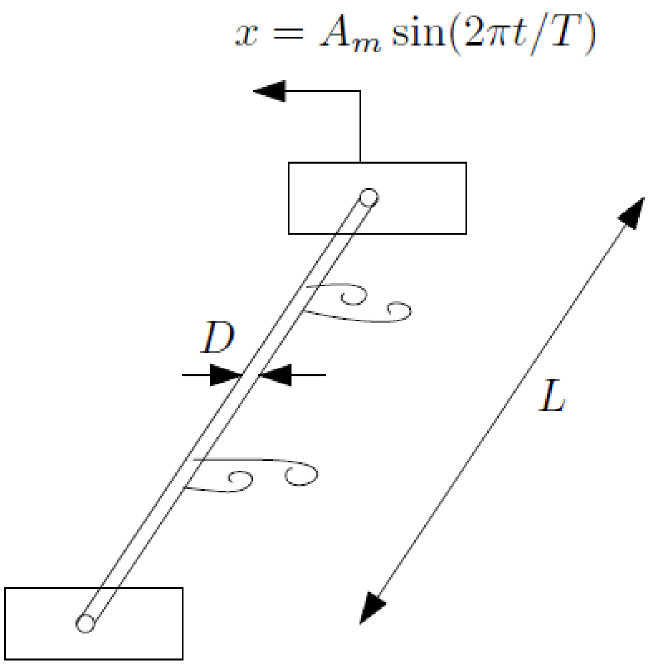


(a) $U_{max} = 0.6\,\mathrm{m/s}$ (b) $U_{max} = 1.3\,\mathrm{m/s}$ (c) $U_{max} = 2.0\,\mathrm{m/s}$ (d) Current profile

solid lines = simulated
diamonds = measured

Results

- Flexible cylinder in oscillating flow
- Experiments by Fu et al. (2014)

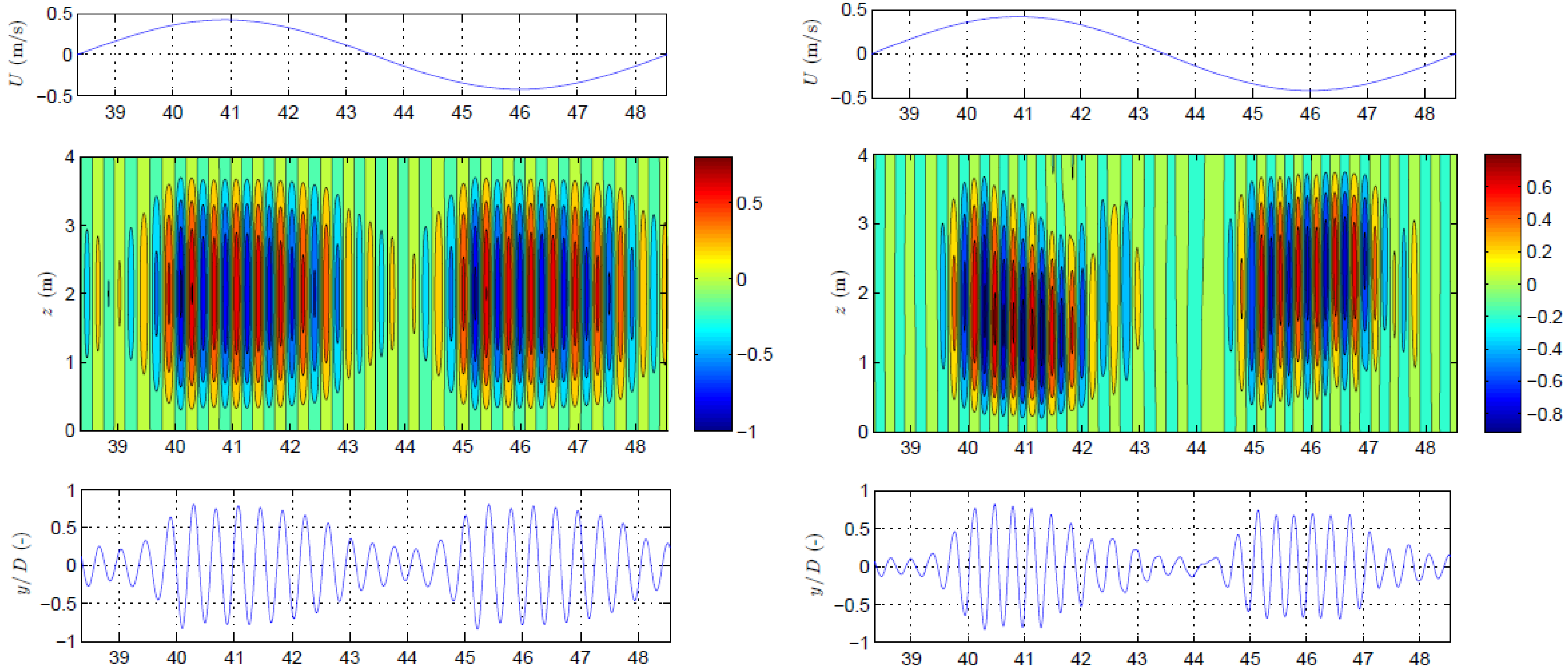


$$\mathrm{KC} = \frac{U_{\max} T}{D} = \frac{2\pi A_m}{D}$$

$$U_{r,\max} = \frac{U_{\max}}{f_1 D} = \frac{2\pi A_m}{T f_1 D} = \frac{\mathrm{KC}}{T f_1}$$

Results

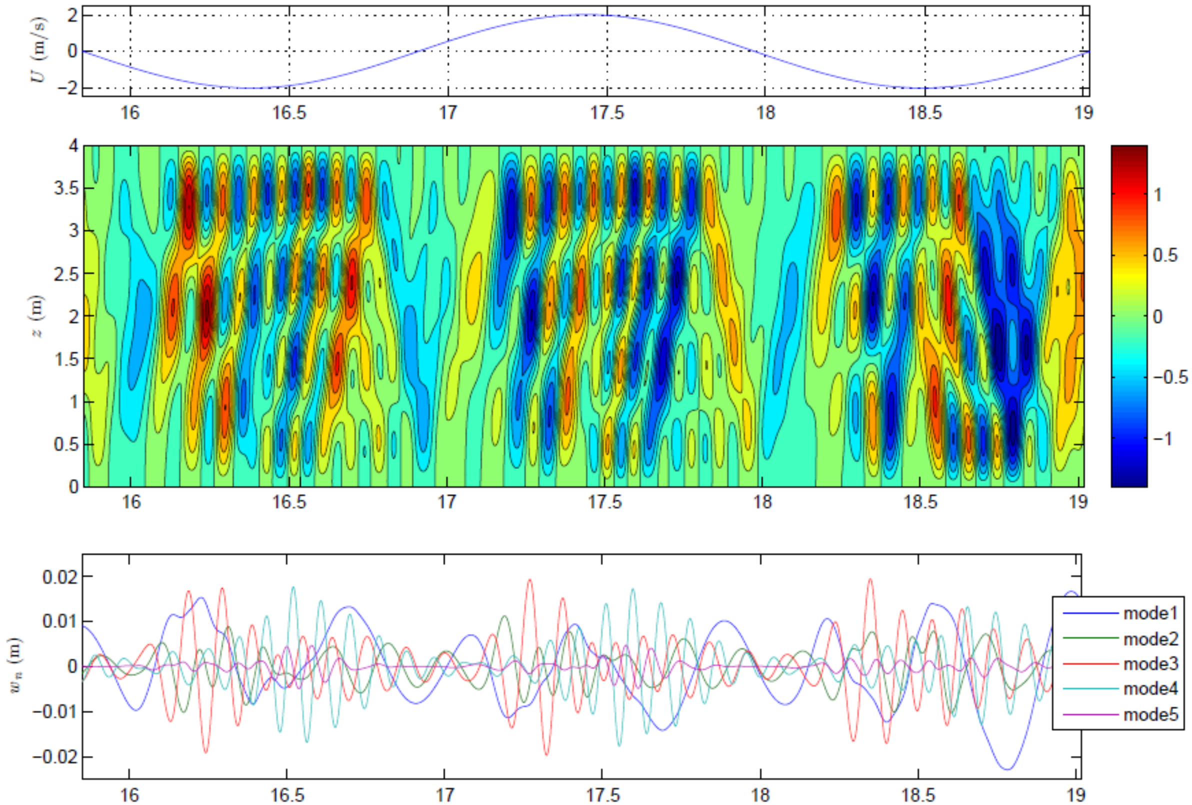
- Flexible cylinder in oscillating flow
- KC = 178, $U_{R,max}$ = 6.5:



(a) Simulation (b) Experiment

Results

- Flexible cylinder in oscillating flow
- Effect of increasing the reduced velocity:



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Concluding remarks

- So far:
  - A time domain model of the hydrodynamic forces relevant to VIV has been established.
  - The model provides realistic results
- Future work:
  - How to combine the model with Morison's eq. to include drag forces? How does drag amplification occur?
  - Other PhD projects:
    - Tor Huse Knudsen: Interaction between VIV and internal flow (deep ocean mining)
    - Jan Vidar Ulveseter: Effect of nonlinear damping (soil or structural)

THANK YOU FOR YOUR ATTENTION!