Savaria Institute of Technology
Faculty of Informatics
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Theoretical and experimental analyses of cables undergoing flow-induced vibrations

by

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NEMZETI KUTATÁSI, FEJLESZTÉSI ÉS INNOVÁCIÓS HIVATAL

AZ NKFI ALAPBÓL MEGVALÓSULÓ PROJEKT

November 4, 2022

Introduction

External effects → Wind
→ Ice formation on the cable
→ Combined effects

vibrations → fatigue → damage

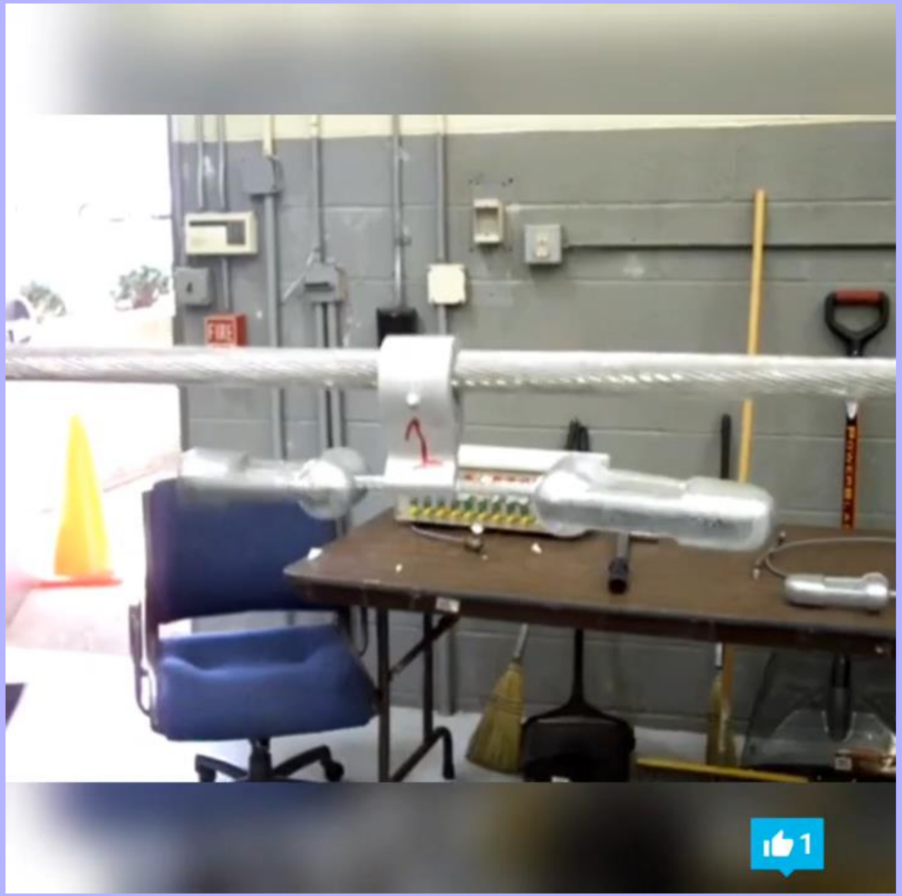
avoid → lab measurements
avoid → analytical modelling

Types of vibrations

Galloping

very **high amplitude** and
low frequency

Aeolian vibration
(*vortex-induced vibration*)



relatively **low amplitude** and
high frequency

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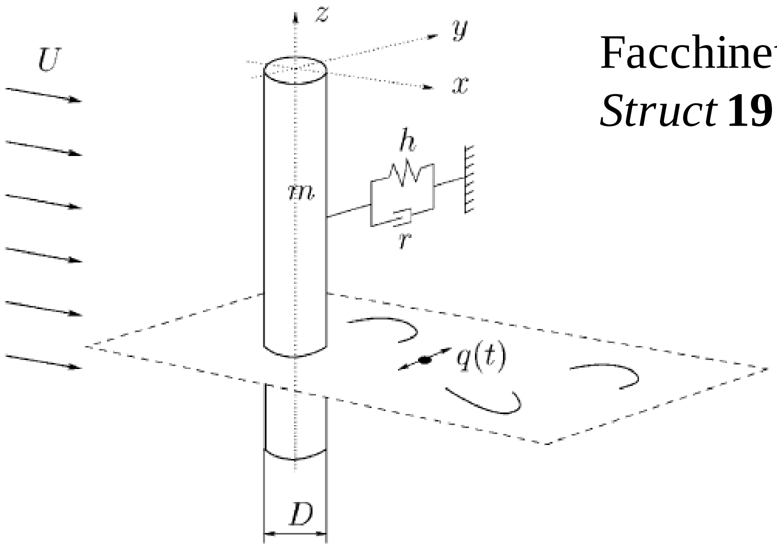
Analytical modelling

Dorogi, D. and Kollár, L.

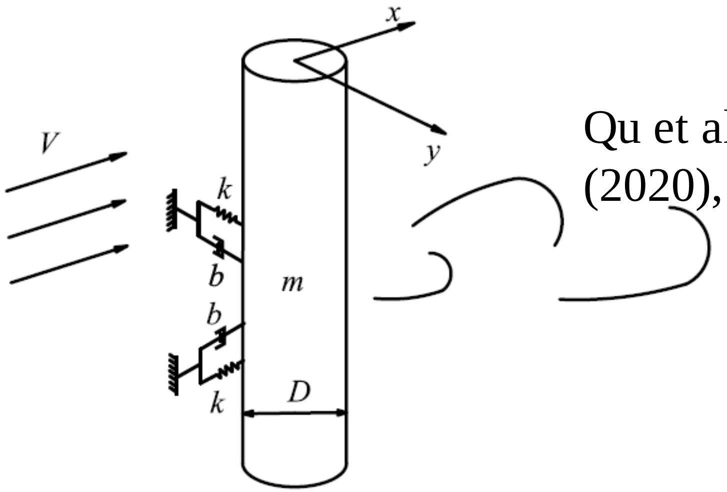
Modelling approaches

1. 1DoF VIV of rigid cylinder (planar problem)



Facchinetti et al, [*J Fluid Struct* **19** (2018), 123]

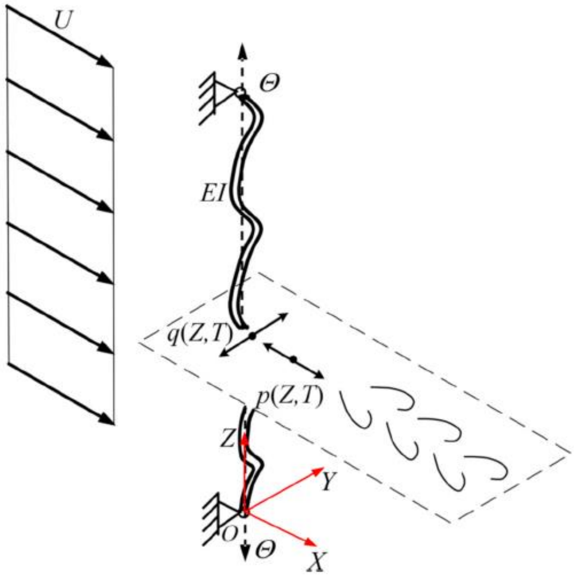
2. 2DoF VIV of rigid cylinder (planar problem)



Qu et al. [*Ocean Eng.* **196** (2020), 106732]

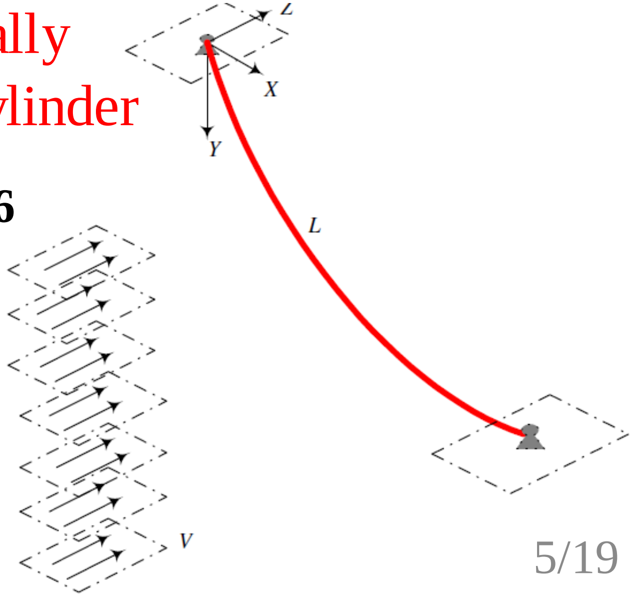
3. FIV of verticle flexible cylinder (3D problem)

Gao et al. [*Mar Struct* **80** (2021), 103078]



4. FIV of geometrically nonlinear flexible cylinder

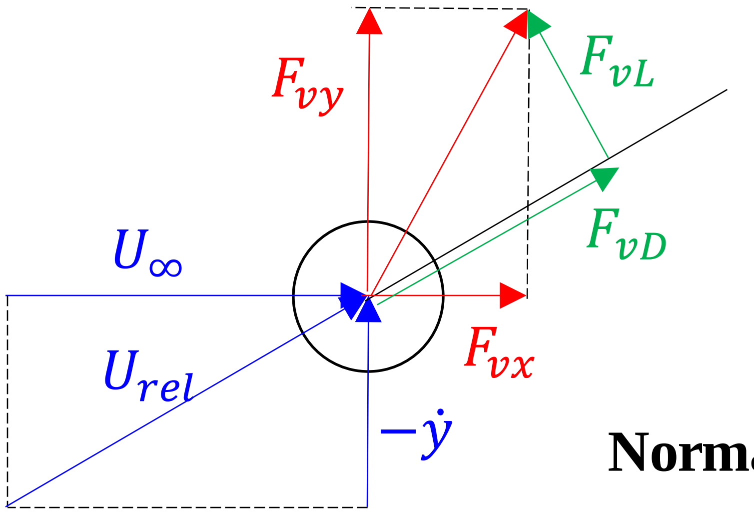
Srinil [*J Fluid Struct* **26** (2010), 1098]



Modeling transverse flow-induced vibrations

$m\ddot{y} + c\dot{y} + ky = F_y(t)$ → $F_y(t) = F_{vy}(t) - m_a\ddot{y}$ → F_{vy} → **drag** (component due to stall)

F_{vy} → **lift**



$$F_{vy} \cong F_{vL} - F_{vD}\dot{y}$$

Normalized form:

$$\ddot{y}^* + \left(2\zeta\Omega_n + \frac{C_{vD}}{4\pi \mathrm{St}\mu}\right)\dot{y}^* + \Omega_n^2 y^* = \frac{C_{vy}}{8\pi^2\mathrm{St}^2\mu} \quad \Rightarrow \quad C_{vL} = \frac{q}{2}C_{L0}$$

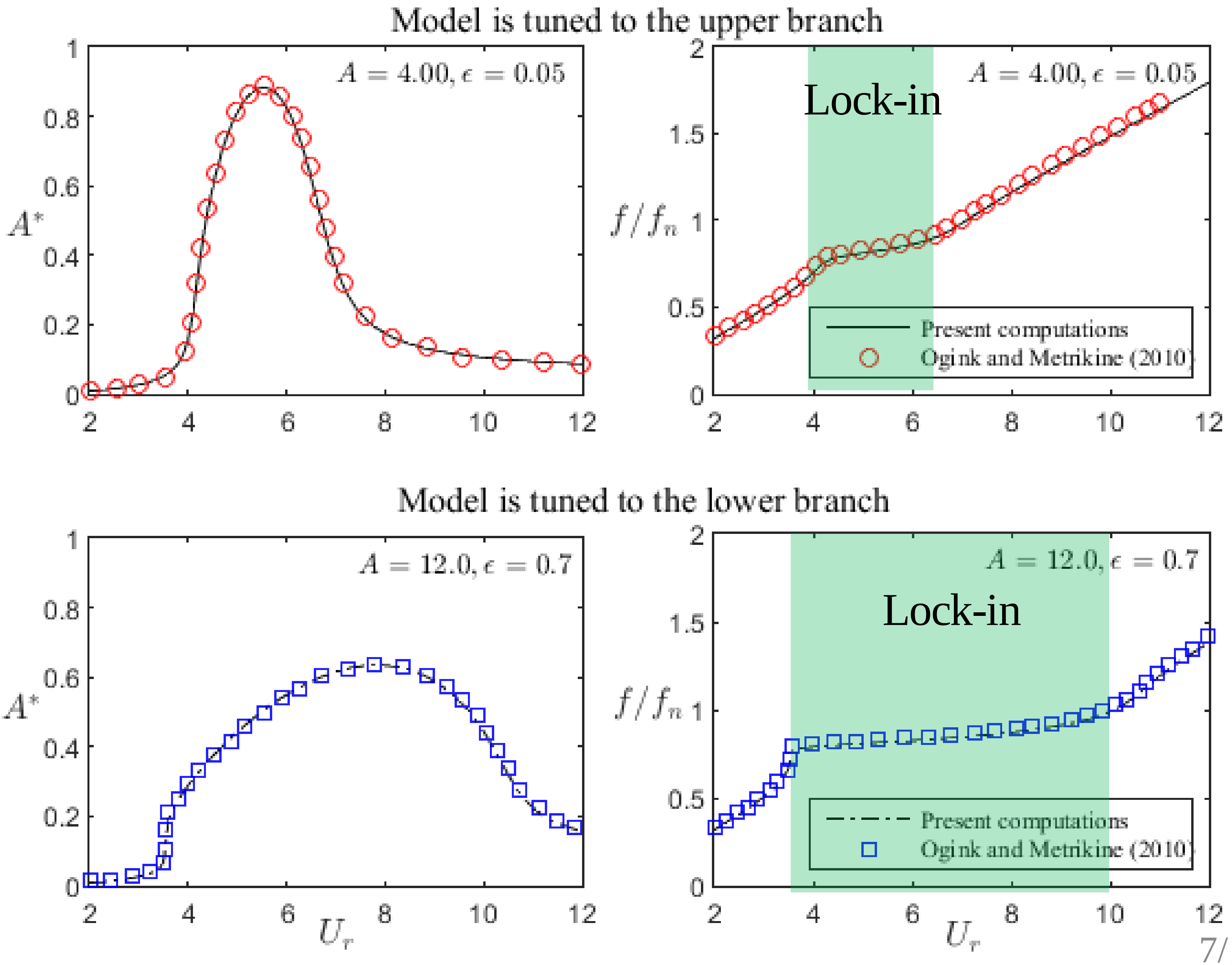
van der Pol equation:

$$\ddot{q} + \epsilon(q^2 - 1)\dot{q} + q = A\ddot{y}$$

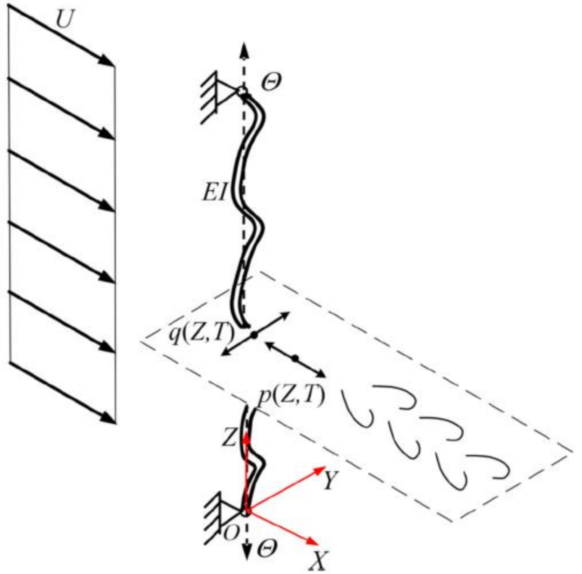
Solved numerically using the FDM

Validation

Empirical parameters (A, ε) have to be properly chosen



Modelling FIV of flexible cylinder



$$\ddot{y}^* + \left(2\zeta\Omega_n + \frac{C_{vD}}{4\pi \mathrm{St}\mu}\right)\dot{y}^* - a^2 y'' + b^2 y^{\mathrm{IV}} = \frac{C_{vy}}{8\pi^2 \mathrm{St}^2 \mu}$$

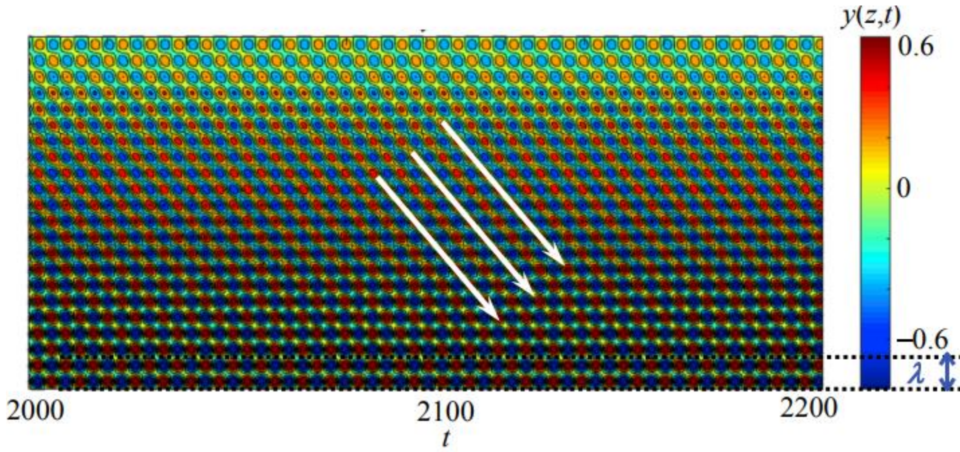
nondimensional

$$\ddot{q} + \epsilon(q^2 - 1)\dot{q} + q = A\ddot{y}$$

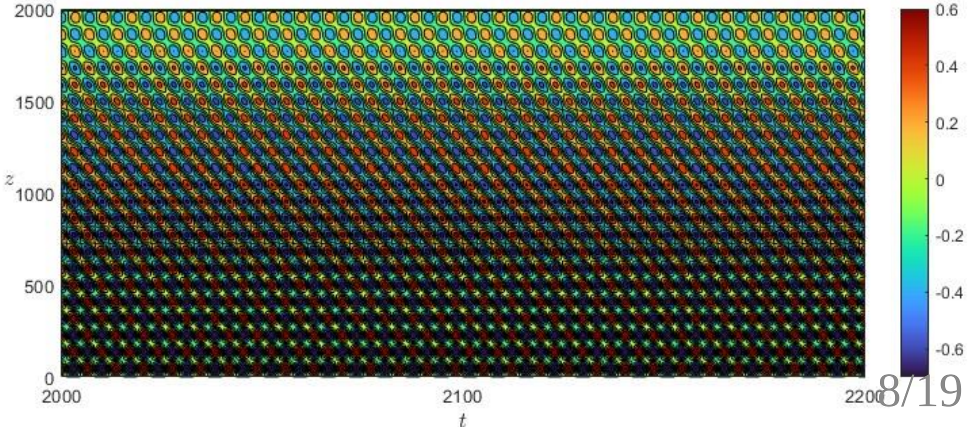
<u>BCs at $x = 0$ and $x = X_H$</u>

$$y = \dot{y} = y'' = 0$$

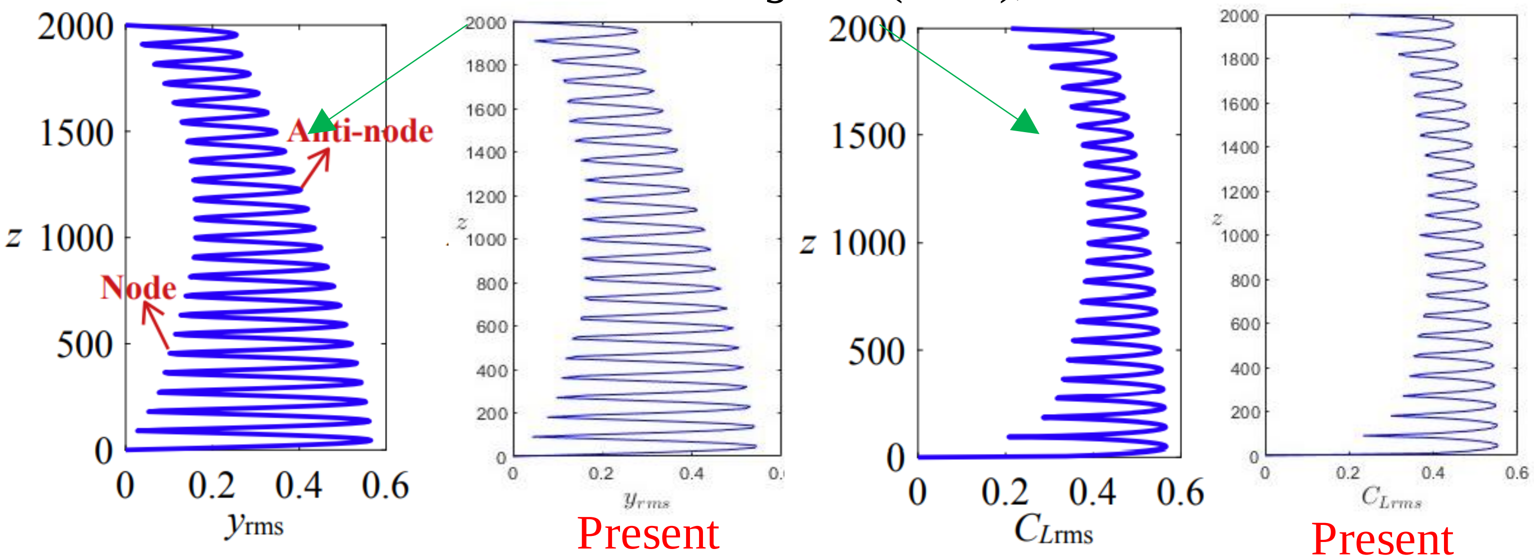
Gao et al. [*Ocean Eng* **171** (2019), 157]



Present



Gao et al. [*Ocean Eng* **171** (2019), 157]



Present

Present

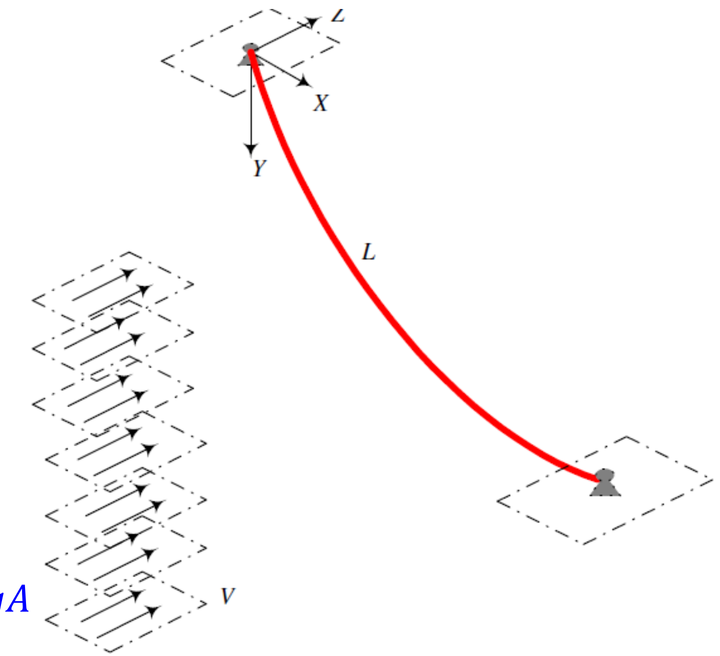
Modelling flexible cylinder with initial curveture

$$m\frac{\partial^2 u}{\partial t^2} + c\frac{\partial u}{\partial t} =$$

$$\frac{\partial}{\partial s}\left\{T\left(\frac{\partial x}{\partial s}+\frac{\partial u}{\partial s}\right) + EA\left[\frac{\partial x}{\partial s}\frac{\partial u}{\partial s} + \frac{\partial y}{\partial s}\frac{\partial v}{\partial s} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial s}\right)^2 + \left(\frac{\partial v}{\partial s}\right)^2\right]\right]\left(\frac{\partial x}{\partial s}+\frac{\partial u}{\partial s}\right) - EI\frac{\partial}{\partial s}\left(\frac{\partial^2 x}{\partial s^2}+\frac{\partial^2 u}{\partial s^2}\right)\right\} + F_x$$

$$m\frac{\partial^2 v}{\partial t^2} + c\frac{\partial v}{\partial t} =$$

$$\frac{\partial}{\partial s}\left\{T\left(\frac{\partial y}{\partial s}+\frac{\partial v}{\partial s}\right) + EA\left[\frac{\partial x}{\partial s}\frac{\partial u}{\partial s} + \frac{\partial y}{\partial s}\frac{\partial v}{\partial s} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial s}\right)^2 + \left(\frac{\partial v}{\partial s}\right)^2\right]\right]\left(\frac{\partial y}{\partial s}+\frac{\partial v}{\partial s}\right) - EI\frac{\partial}{\partial s}\left(\frac{\partial^2 y}{\partial s^2}+\frac{\partial^2 v}{\partial s^2}\right)\right\} + F_y + \rho_c g A$$

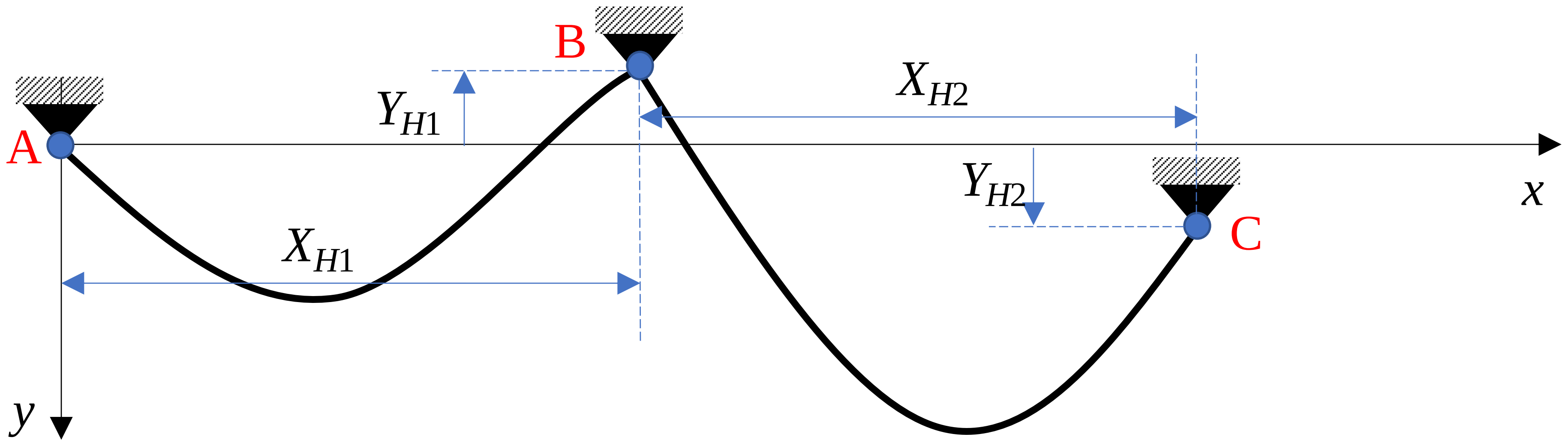


$$\frac{\partial}{\partial s} \rightarrow \frac{\partial}{\partial x}$$

$$m\ddot{u} + c\dot{u} - \frac{1}{k}\left\{\frac{T}{k}(1+v') + \frac{EA}{k^3}(u'+y'v') + \frac{EA}{k^3}\left[u'^2 + y'u'v' + \frac{1}{2}(u'^2+v'^2)\right] + \frac{EA}{2k^3}(u'^3+u'v'^2)\right\}' + \frac{EI}{k^3}(1+u^{\mathrm{III}})' = F_x$$

$$m\ddot{v} + c\dot{v} - \frac{1}{k}\left\{\frac{T}{k}(y'+v') + \frac{EA}{k^3}(u'y'+y'^2v') + \frac{EA}{k^3}\left[u'v' + y'v'^2 + \frac{y^2}{2}(u'^2+v'^2)\right] + \frac{EA}{2k^3}(u'^2v'+v'^3)\right\}' + \frac{EI}{k}\left[\frac{1}{k^3}(y^{\mathrm{III}}+v^{\mathrm{III}})\right]' = F_y + \rho_c g A$$

Initial conditions



Limiting case (static equillibrium):

$$EIy^{\mathrm{IV}} - T_H y'' = 0$$

Boundary conditions at points A, B, and C

$$y = y'' = 0$$

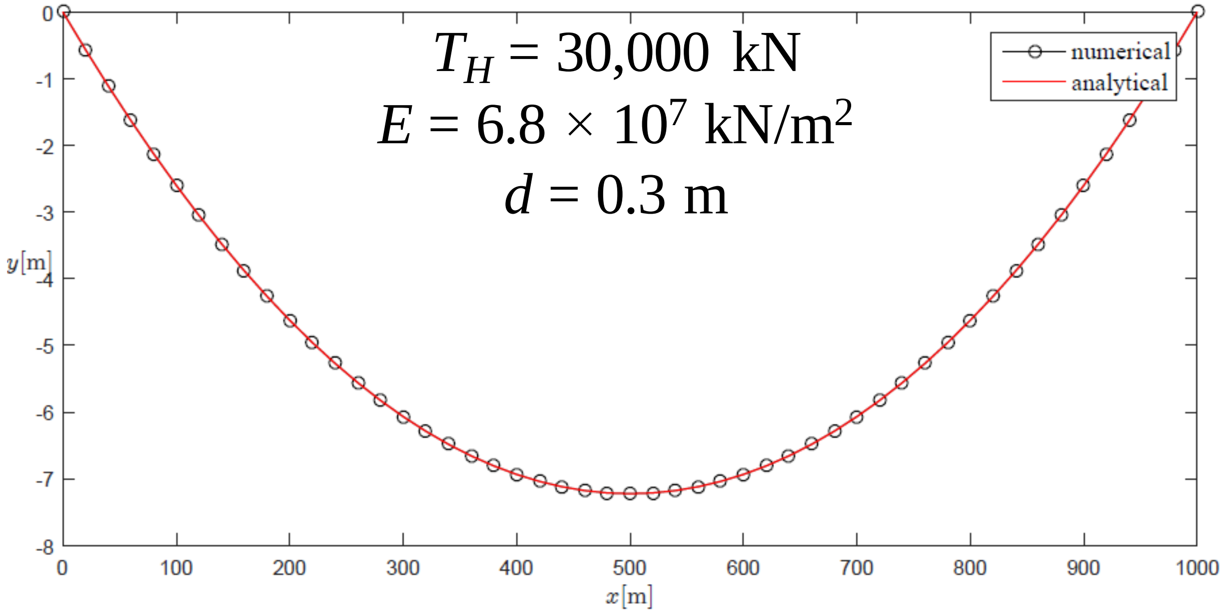
Analytical solution:

$$y_{an}(x) = \frac{T_H}{\rho_c g A}\left\{\cosh\frac{\rho_c g A X_{Hi}}{2T_{Hi}} - \cosh\left[\frac{\rho_c g A}{T_{Hi}}\left(\frac{X_{Hi}}{2} - x\right)\right]\right\}$$

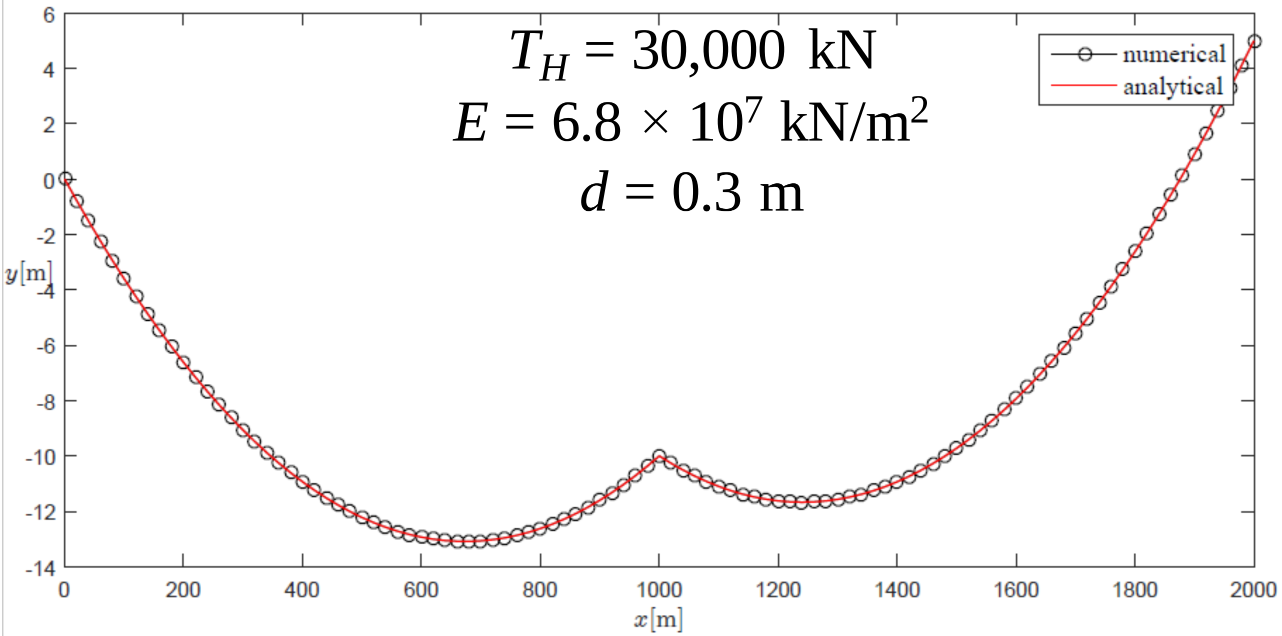
Srinil et al. [*Nonlinear Dyn* **48** (2007), 231]

Comparison against analytical result

Single-span cable



Double-span cable



The agreement between numerical and analytical solutions is very good

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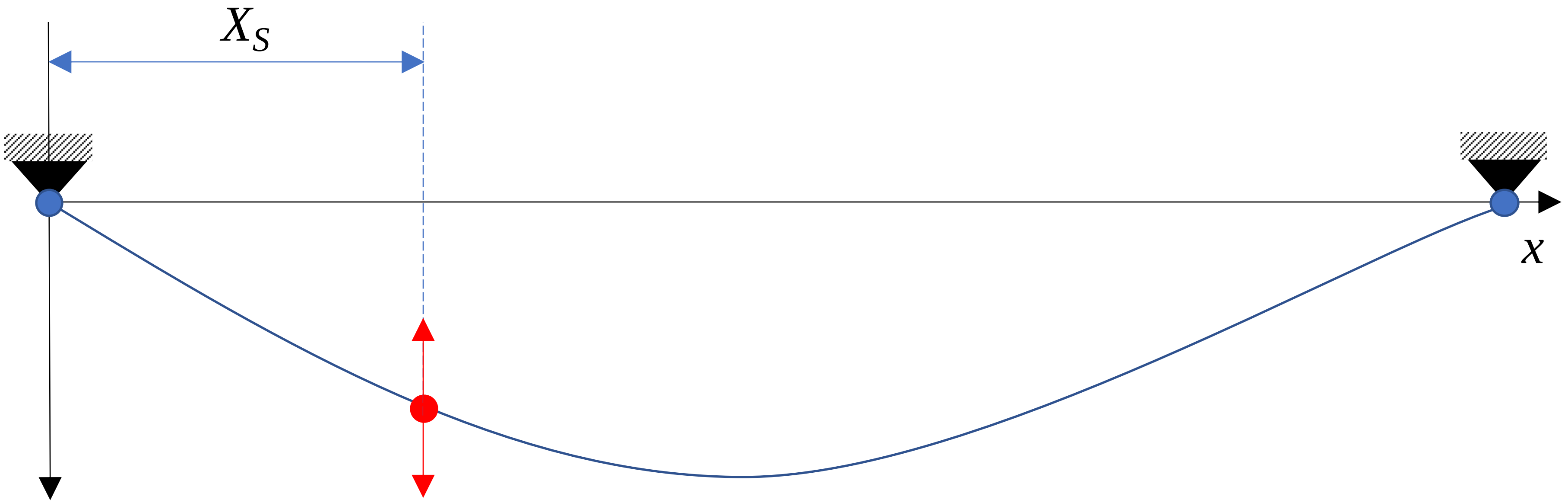
Laboratory measurements

Utkarsh, S.P., Dorogi, D. and Kollár, L.

Shaker tests (exp. setup)



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

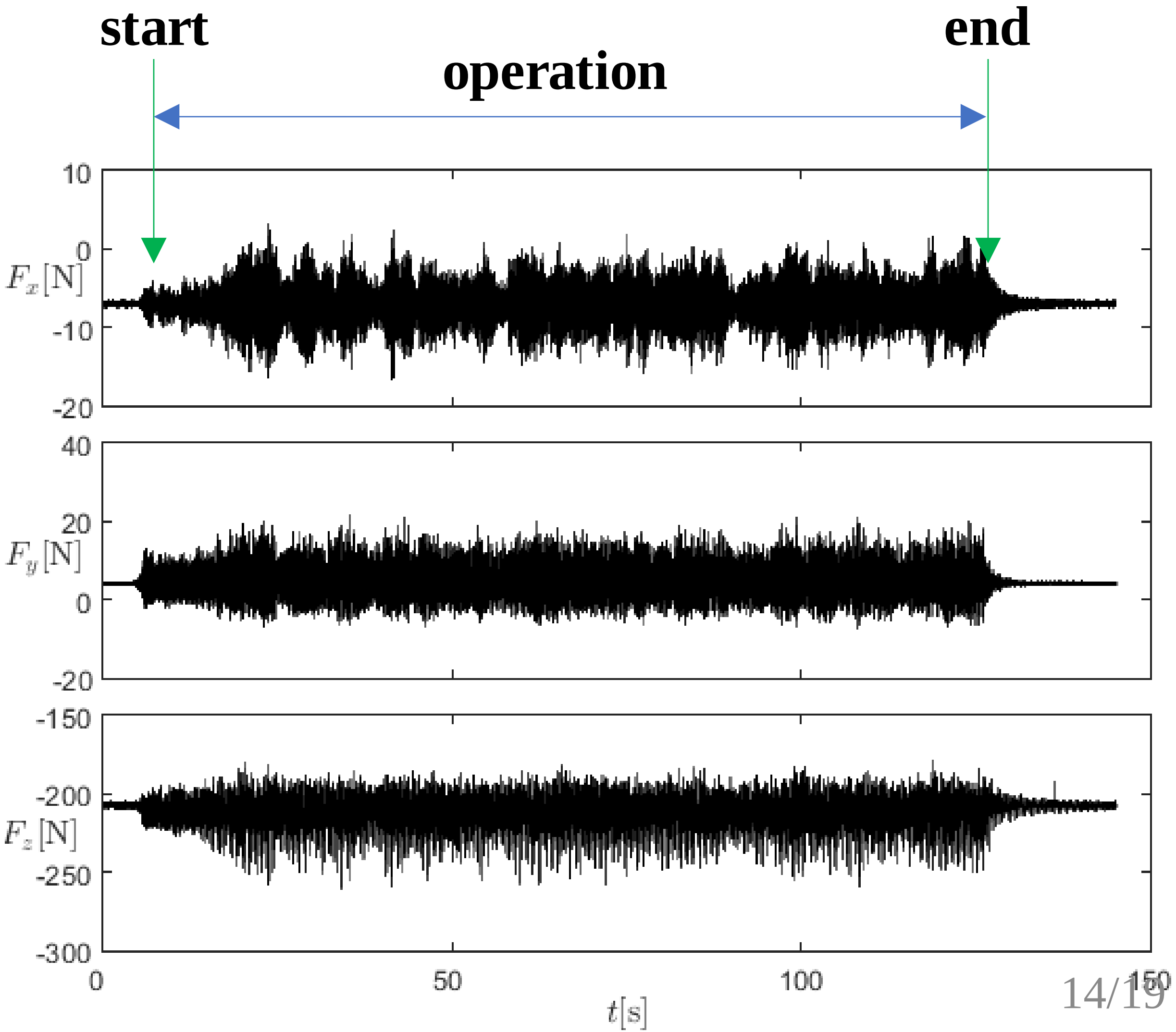
?? forces at the first suspension point: F_x, F_y, and F_z

evaluate data using advanced data processing techniques

make comparison against analytical results

Forces

(A = 5mm, f = 20 Hz)



Aeolian vibration

Galloping

Next steps

A1. Develop a model for single-span cable (the cable is forced to vibrate at a single point)

M1. Force measurement for single-span cable

A2. Develop a model for double-span cable (the cable is forced to vibrate at a single point)

M2. Force measurement for double-span cable

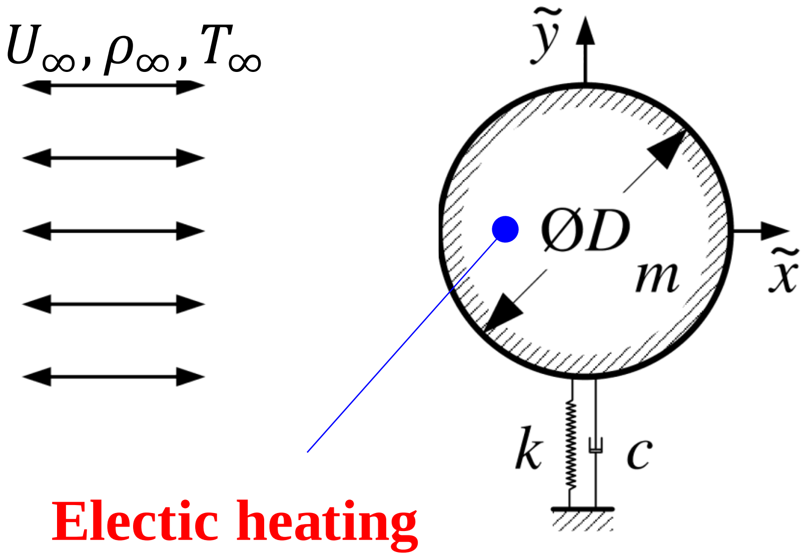
A4. Aerodynamic model for flexible cables

M3. Wind-tunnel measurements for flexible cables

A3. Simulate flow-induced vibration of single and double-span cables

Measurements in wind tunnel

M4. Thermal effects on VIV of a single circular cylinder



– wind tunnel measurements

– combined effects of free stream **velocity** U_∞ and stream **temperature** T_∞ on fluid forces and cylinder response

?? design the cylinder support

?? oscillation amp. and freq.: post-processing data from accelerometer

?? force measurements: load cells

?? time-resolved velocity measurements in the wake

Other activities

1. Extend the collaboration with Prof Efstathios Konstantinidis to cable dynamics field

2. Develop a prediction approach for streamwise vortex-induced vibration (invited paper to the special issue of *Journal of Fluids and Structures*)

3. Work on two journal papers in the field of *vortex-induced vibrations of a circular cylinder placed into oscillatory flow*

Thank you for your kind attention

contact information

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