Inverse Analysis of VIV Experiments

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Outline

- Background
- Objective
- Methodology
- Application
- Conclusions

VIV and Offshore Structures

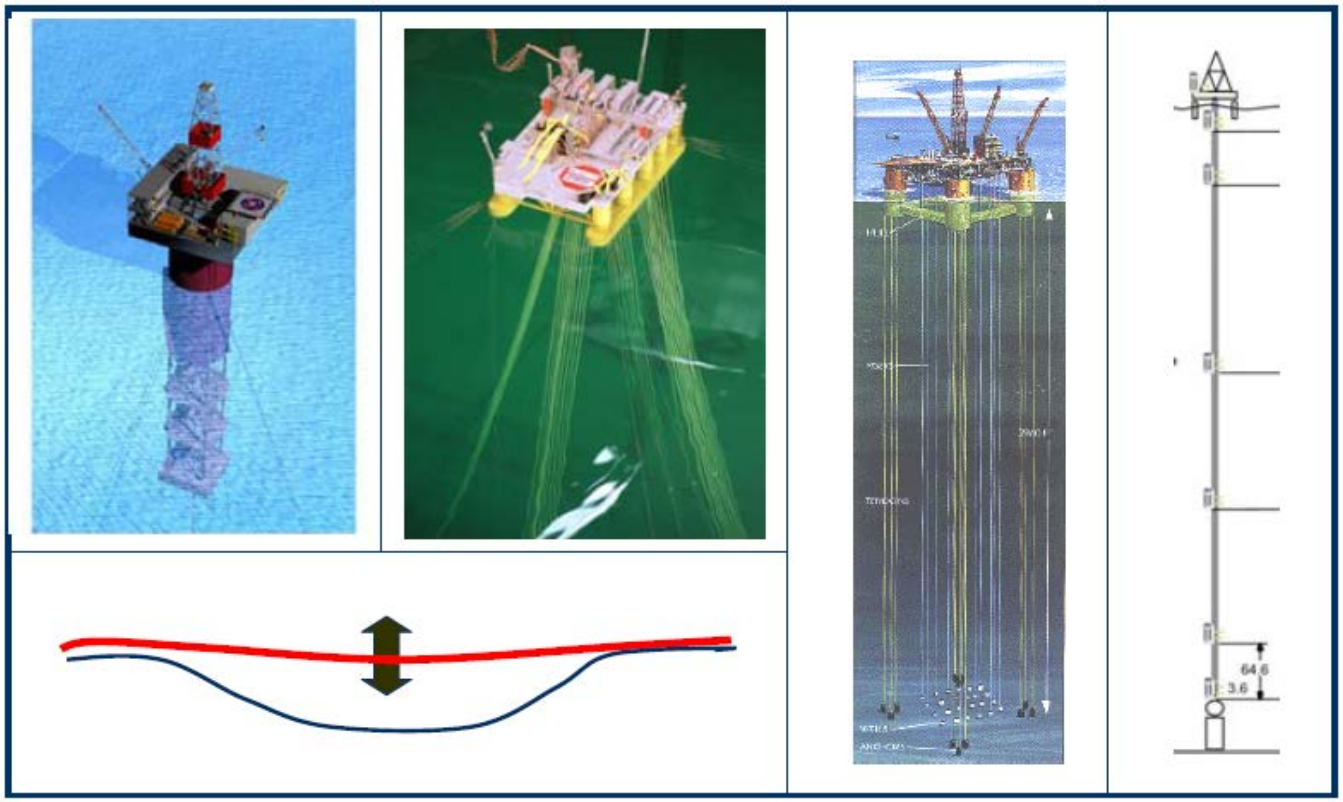


Figure from Baarholm

- Fatigue damage
- Amplified drag force

Empirical VIV Prediction Models

- Industrial tools:
  - VIVANA, Larsen
  - SHEAR7, Vandiver
  - VIVA, Triantafyllou
- Hydrodynamic Force Model
  - Empirical hydrodynamic force coefficient database
  - Rigid cylinder VIV test

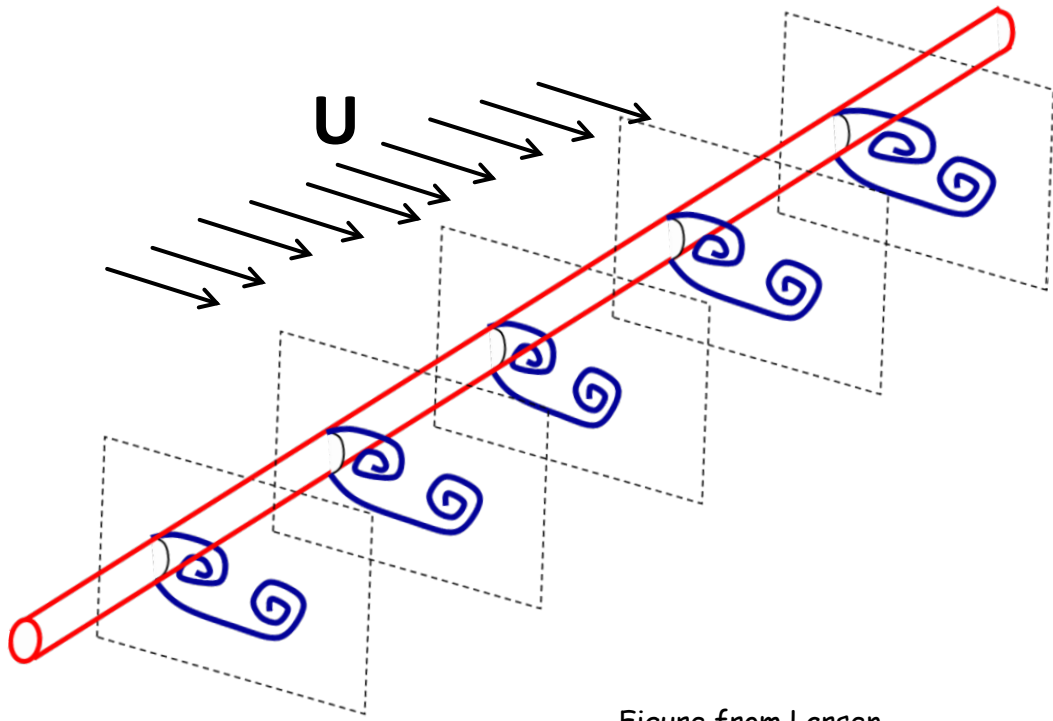


Figure from Larsen

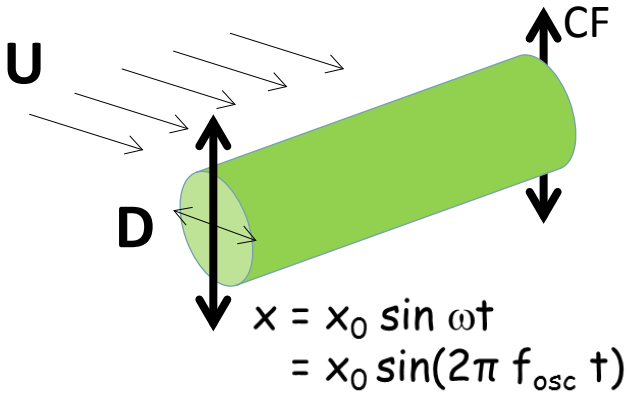
Hydrodynamic Force Coefficient Database

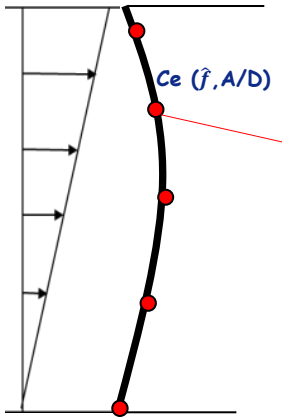
2D Rigid Cylinder VIV Test

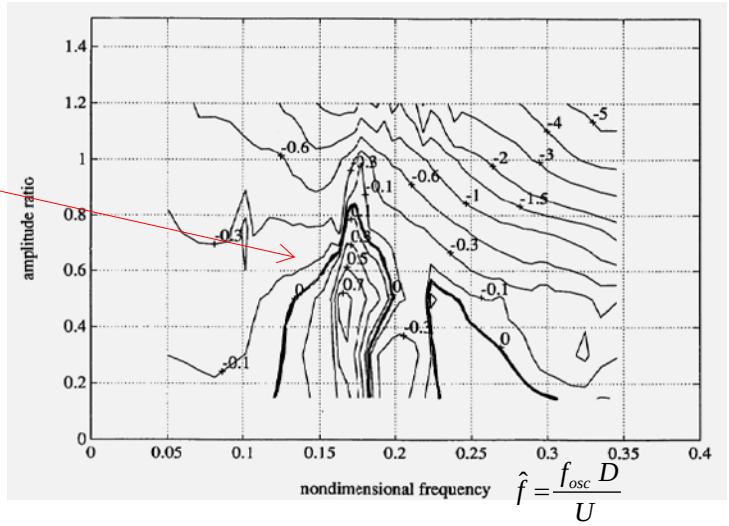
- Forced Harmonic Motions
- Forces are directly measured
- Excitation coefficient, Ce
- Added mass coefficient, Ca

Force coefficient database

- Ce ($\hat{f}$, A/D)
- Ca ($\hat{f}$, A/D)

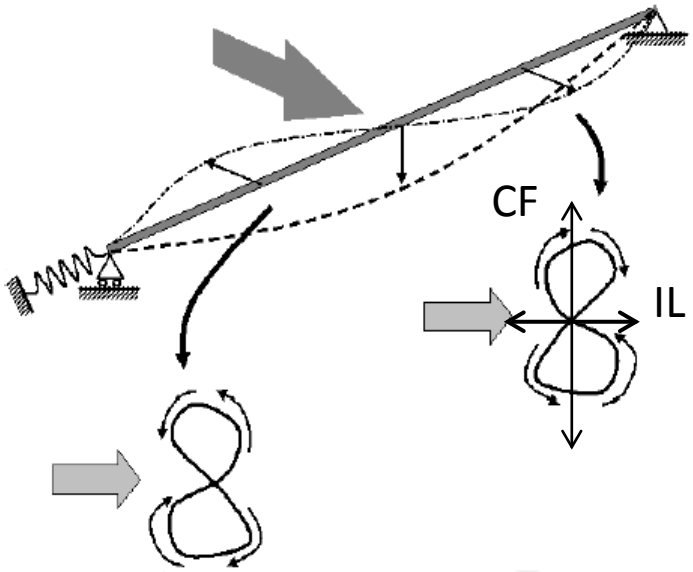






Gopalkrishnan, 1993

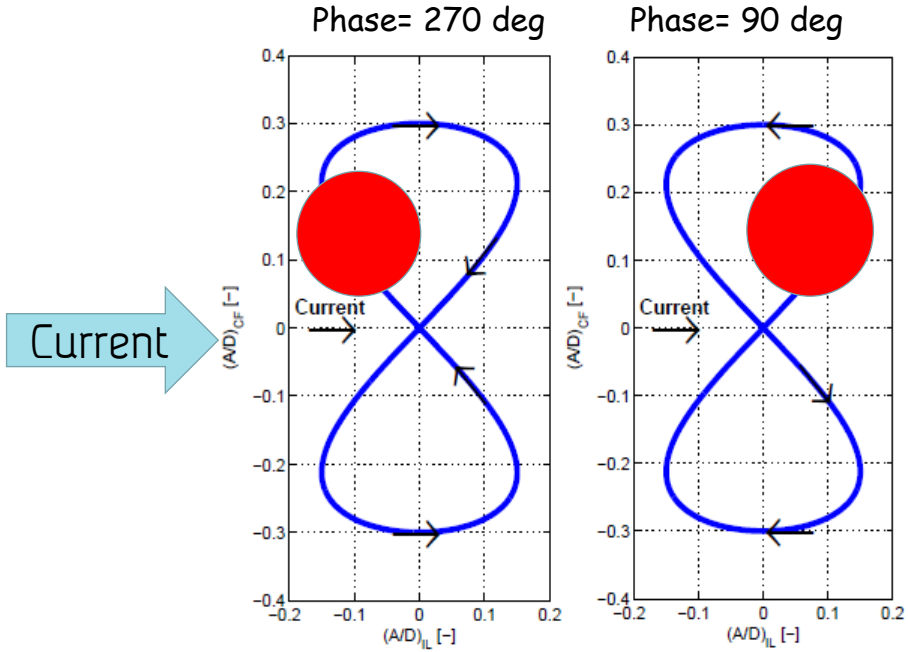
IL and CF Interaction



(a) Schematic illustration

There is still lack of a complete load interaction model

Rigid cylinder forced motion test



(b) Tested orbitals

Aronsen, et al (2007)

3D VIV Experiments with Flexible Cylinders

- Experiments (1997 - 2012)
  - Rotating Rig Tests
  - Hanøytangen Test
  - Ormen Lange Test
  - NDP High Mode VIV Test
  - MIAMI Tests
  - Shell VIV Tests
  - Other tests…

- Uniform or sheared flow
- With/without suppression devices
- Response frequency, amplitudes, and modal information are often analyzed

No direct force measurements along the flexible cylinder

Acceleration or/and bending strain measurements

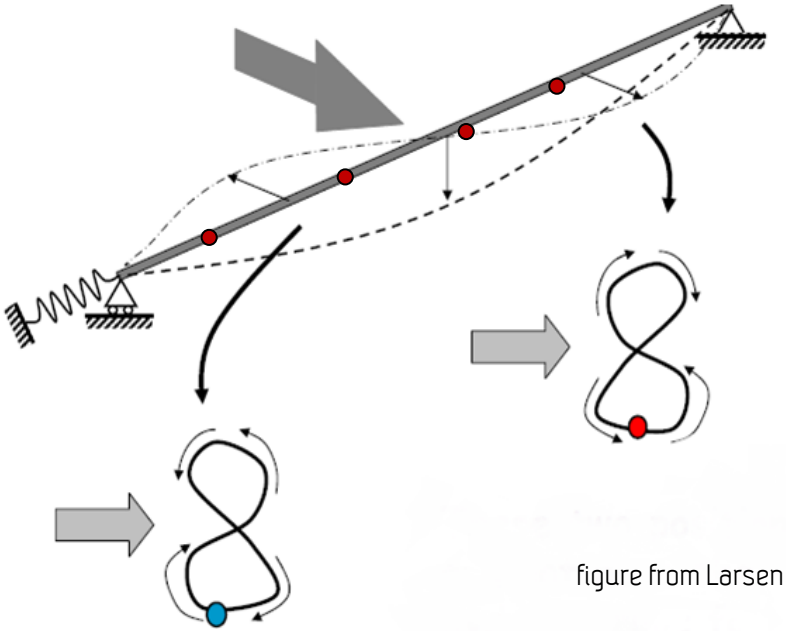
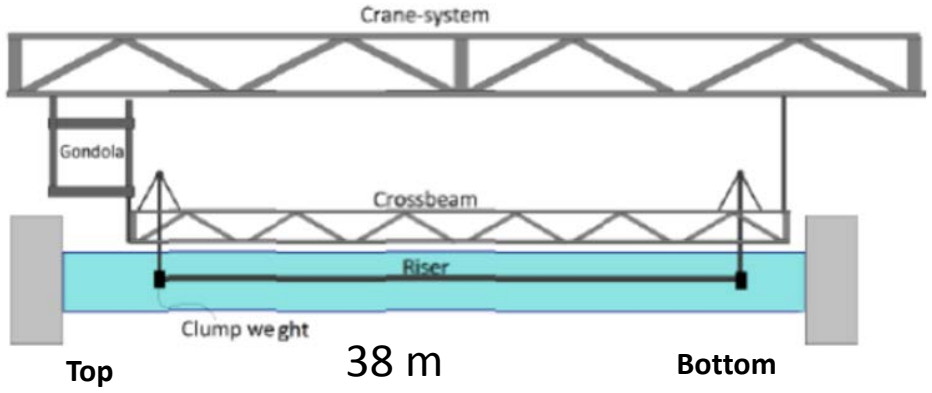
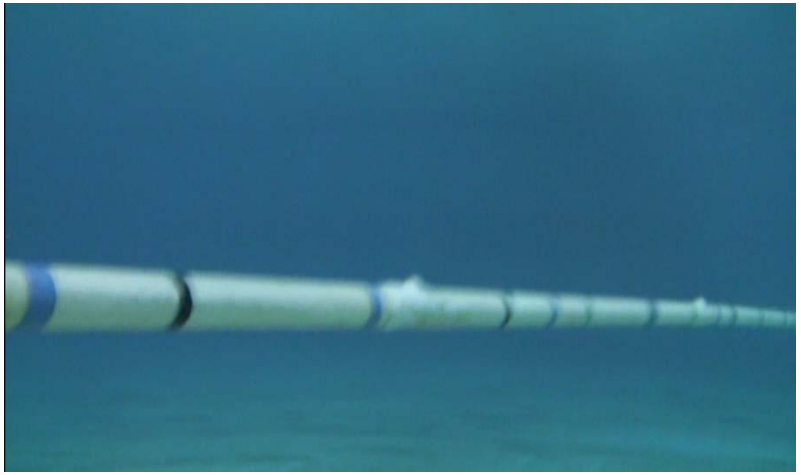


figure from Larsen

3D VIV Experiments with Flexible Beams





No direct force measurements along the flexible cylinder

Research Objectives

- Obtain a tool to identify hydrodynamic forces/coefficients from VIV experiments with flexible cylinders
- Improve the existing force model/force coefficient database in empirical programs
- Understand better VIV loading mechanism of flexible cylinders – IL and CF interaction

Hydrodynamic Force Identification by Inverse Analysis

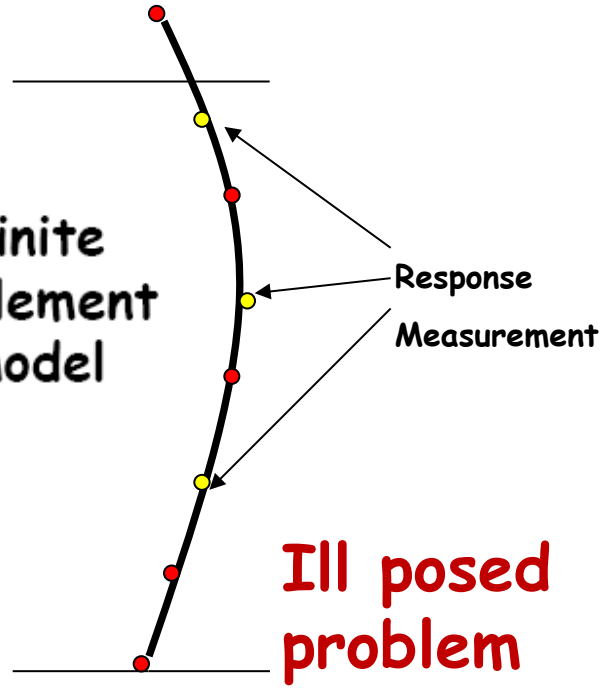
The Dynamic Equilibrium Equation

Structural Mass | Structural Damping | Structural Stiffness | Hydrodynamic forces

$$M\ddot{r} + C\dot{r} + Kr = R$$

Identify hydrodynamic forces along the pipe

Method 1: Direct Inverse Analysis
Method 2: Inverse Analysis based on Optimal Control Theory



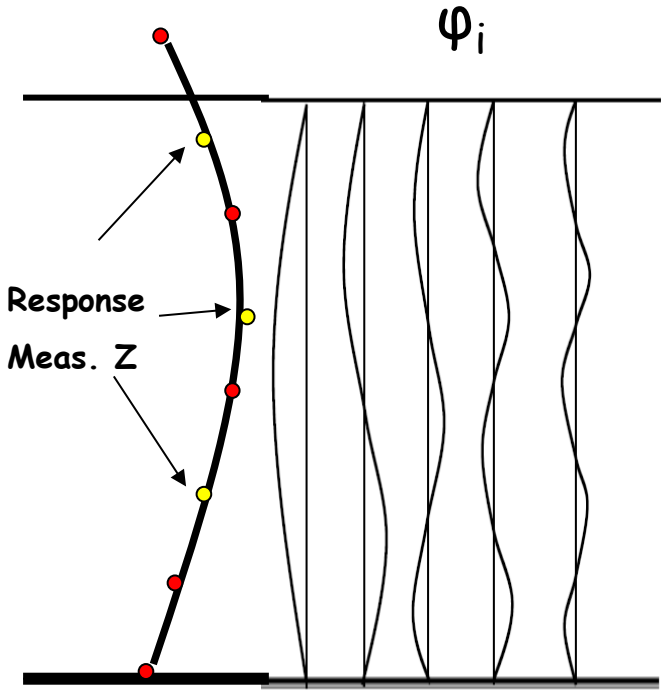
Method 1: Direct Inverse Analysis

Response Reconstruction from Measurements by Modal Approach

$$Z(t) = \sum_{n=1}^{\infty} w_n(t)\varphi_n \qquad or \qquad \mathbf{Z} = \mathbf{\Phi}^T\mathbf{w}$$

$$\mathbf{w} = \left(\mathbf{\Phi}^T\mathbf{\Phi}\right)^{-1}\mathbf{\Phi}^T\mathbf{Z}(t)$$

$$\mathbf{r} = \overline{\mathbf{\Phi}}\mathbf{w}$$



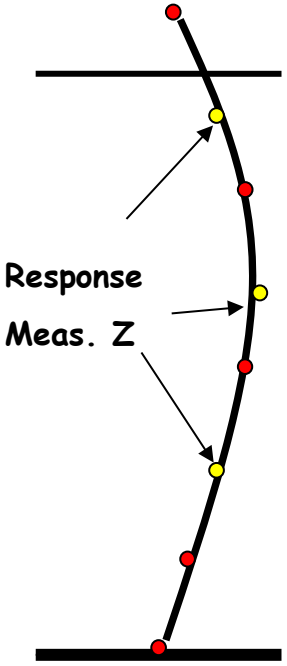
Estimate Forces along the Pipe

$$\mathbf{M}\ddot{\mathbf{r}} + \mathbf{C}\dot{\mathbf{r}} + \mathbf{K}\mathbf{r} = \mathbf{R}$$

Method 2: Inverse Analysis Based on Optimal Control Theory

State Space Form of Dynamic Equilibrium Equation

$$\dot{\mathbf{X}}(t) = \mathbf{A}\ddot{\mathbf{X}}(t) + \mathbf{B}\mathbf{F}(t)$$
$$\mathbf{Z}(t) = \mathbf{G}\mathbf{X}(t)$$



Cost Functions

$$j_Z(t) = \frac{1}{2}(Z_0 - Z)^T Q_{ZZ}(Z_0 - Z), \quad \text{where} \quad Q_{ZZ} = \frac{1}{\sigma_z^{\,2}} I$$

$$j_F(t) = \frac{1}{2} F^T Q_{FF} F, \quad \text{where} \quad Q_{FF} = \frac{1}{\sigma_F^{\,2}} I$$

Solving Constrained Optimization

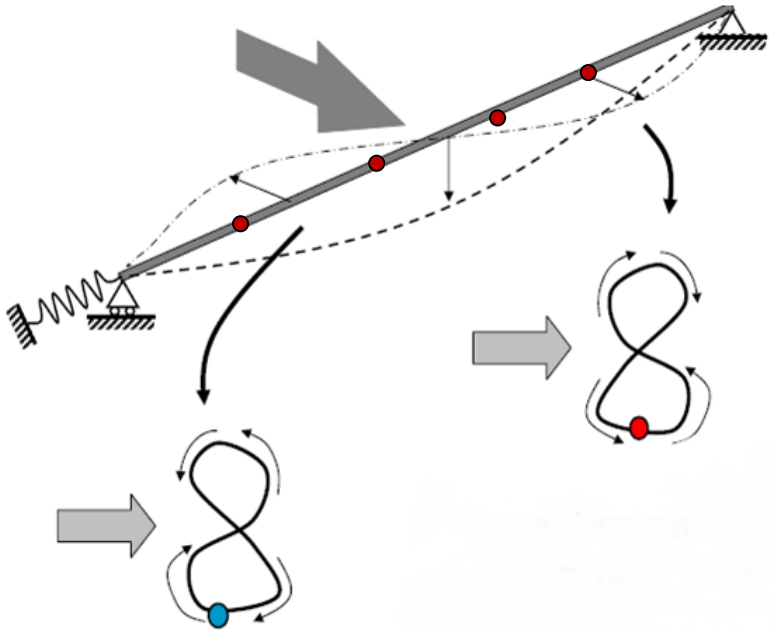
$$J = \int \left(\frac{1}{2} X^T Q_{XX} X + Q_X X + \frac{1}{2} F^T Q_{FF} F \right) dt, \quad \min_{X,F} J \ \textit{subjected to} \ \dot{X}(t) = A\ddot{X}(t) + BF(t)$$

Application of Inverse Analysis on VIV Experiments with Flexible Cylinders

Acceleration or/and bending strain measurements

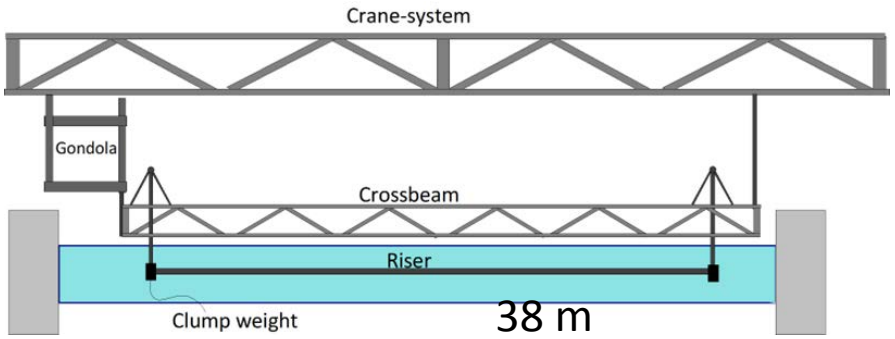
Identify hydrodynamic forces/coefficients from VIV experiments with flexible cylinders

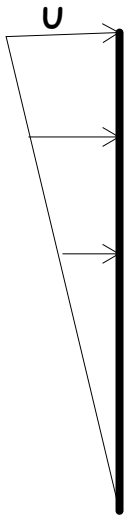
- Rotating Rig Test, 1996, 2003
- Hanøytangen Test, 1997
- NDP High Mode VIV Test, 2003
- Shell VIV Test, 2011

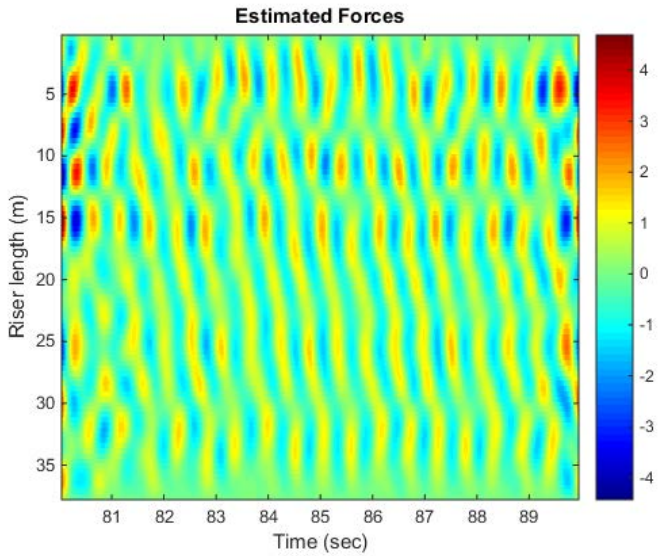


Application – Force Identification

Shell VIV Test, 2011

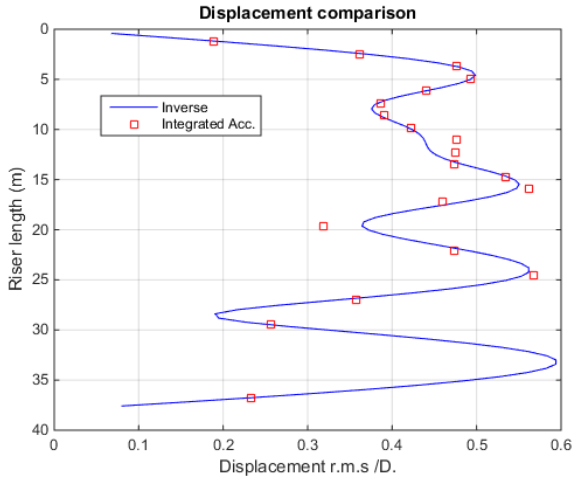


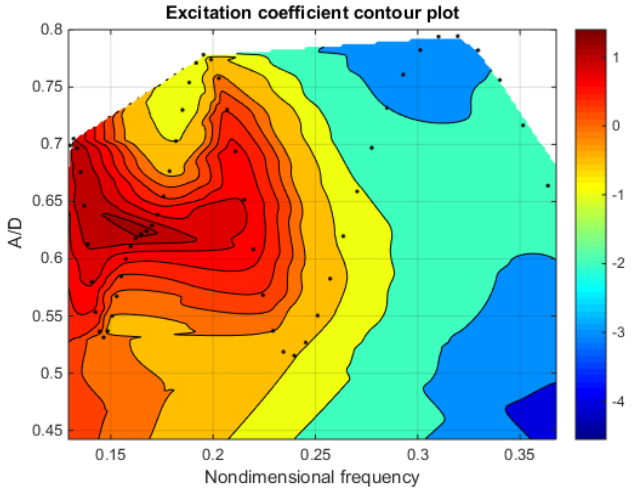




- **CF response measurements:**

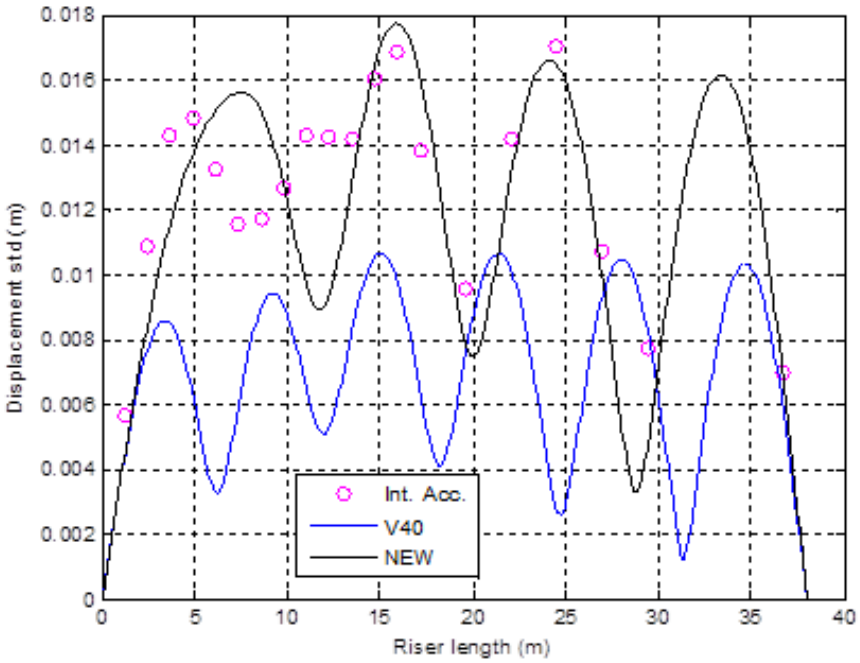
  22 accelerometers
  30 strain measurements



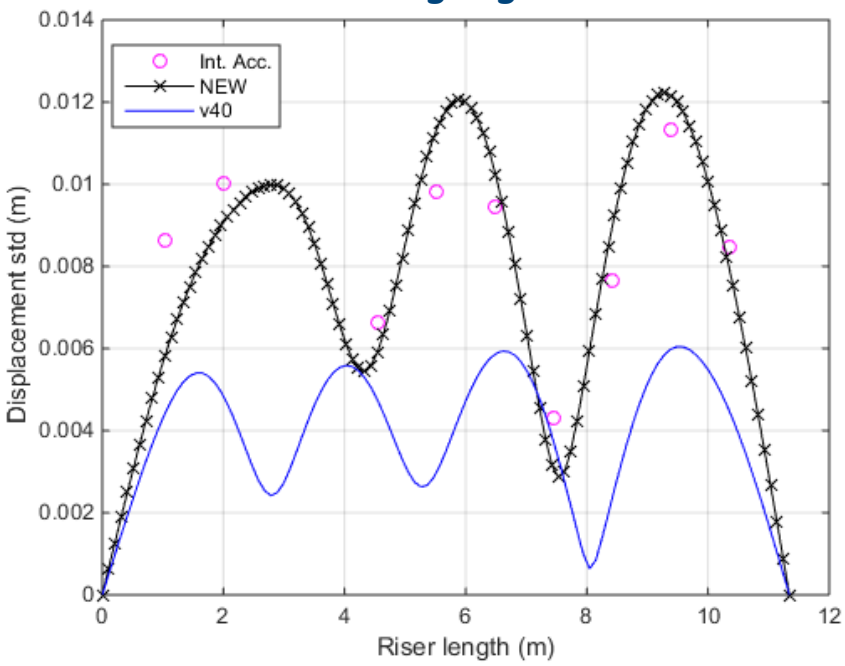


Application – VIVANA Prediction

Shell VIV Test

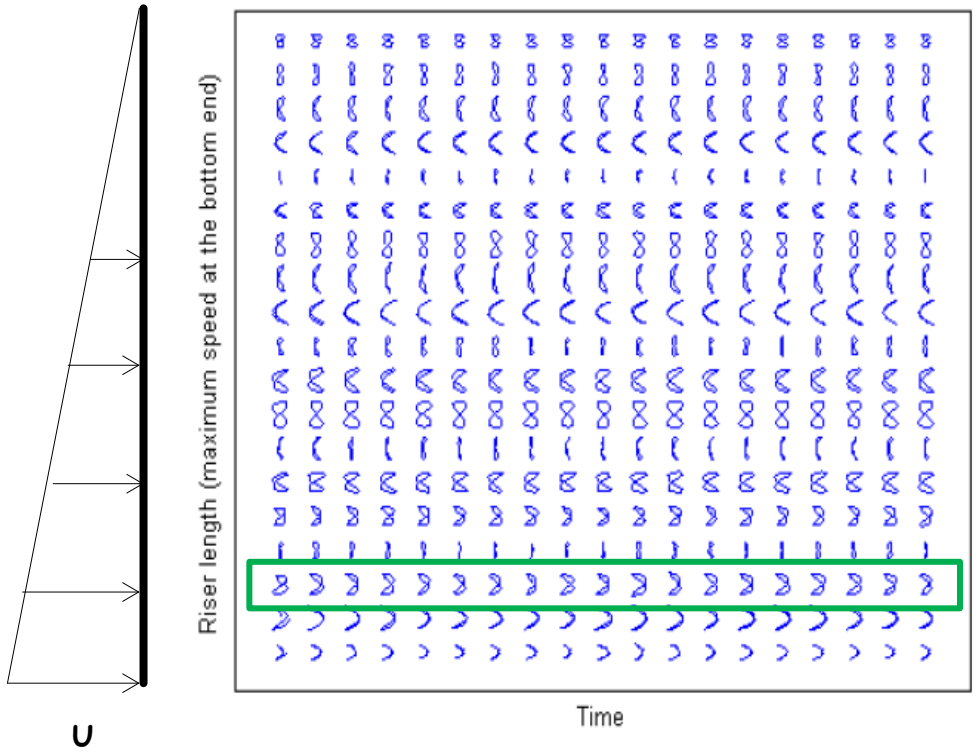


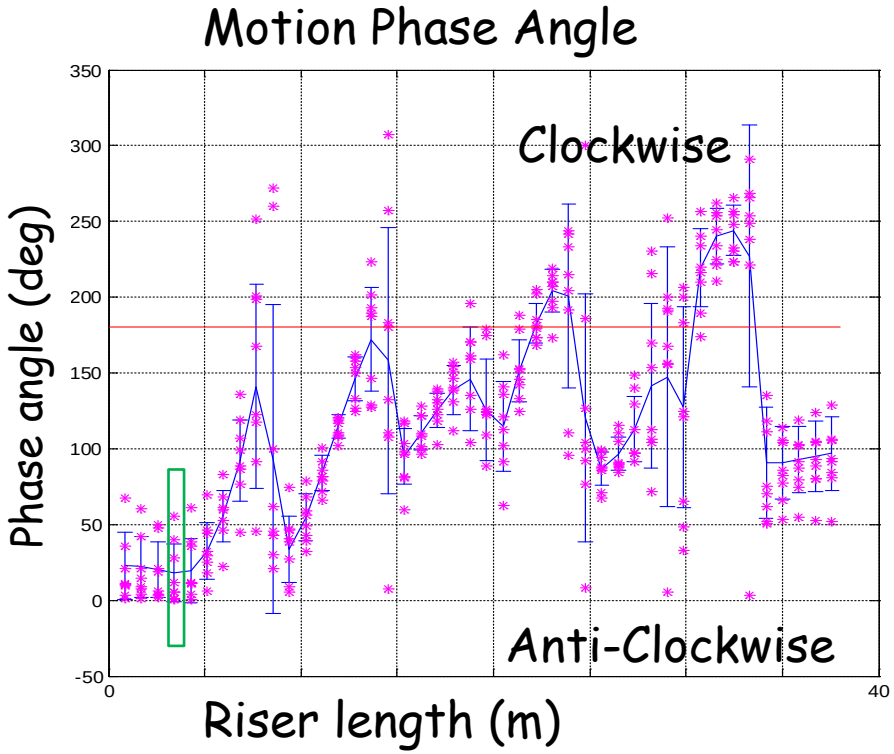
Rotating Rig Test



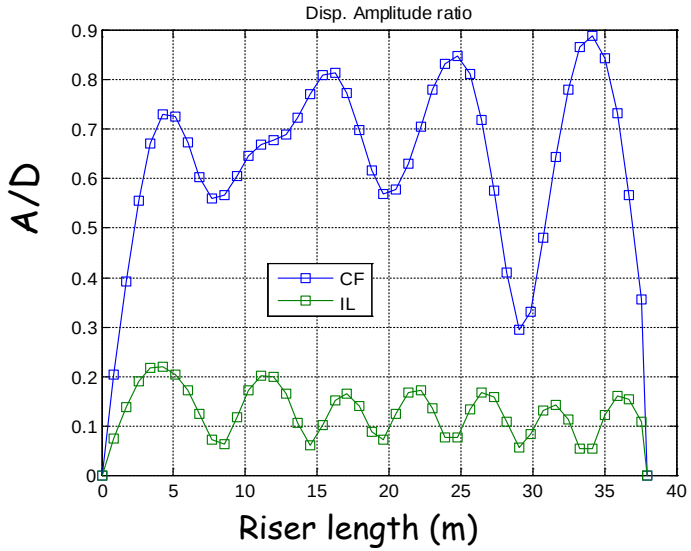
- Correct response frequency
- Improvement in response prediction

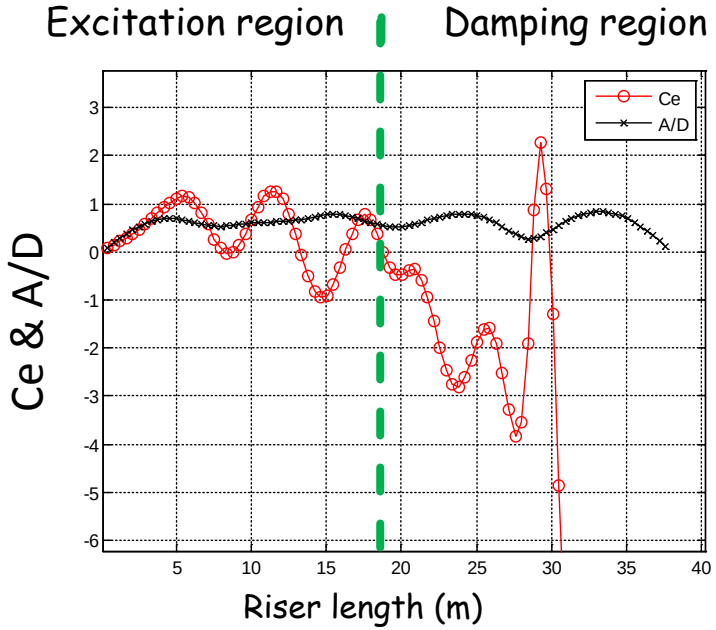
Application – IL and CF Interaction



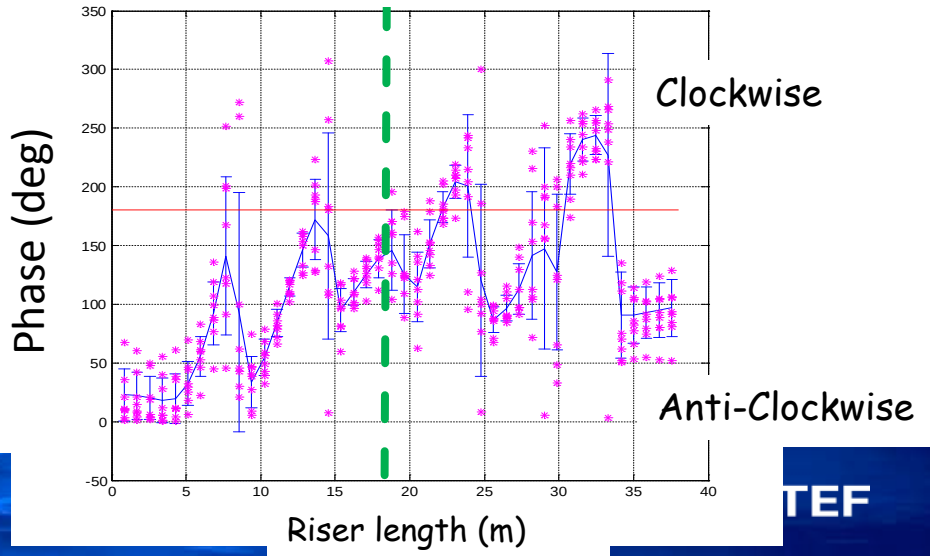


Application – IL and CF Interaction

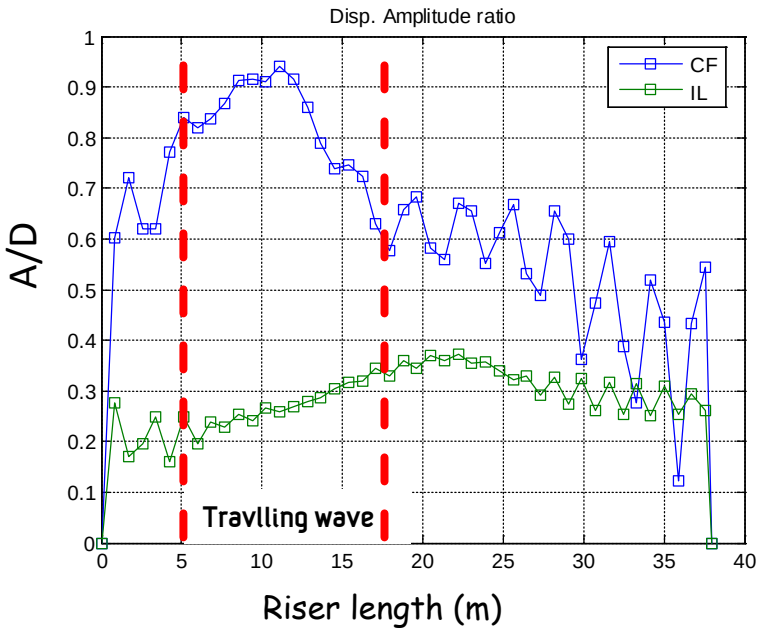


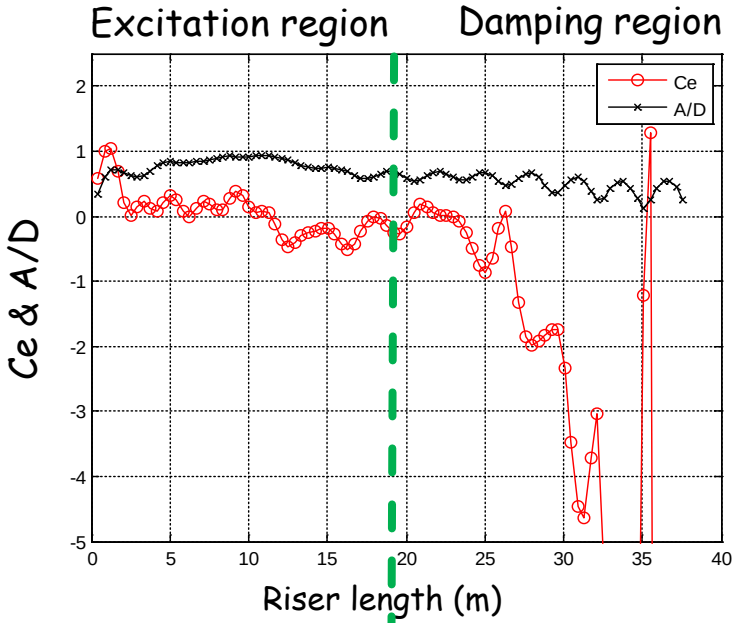


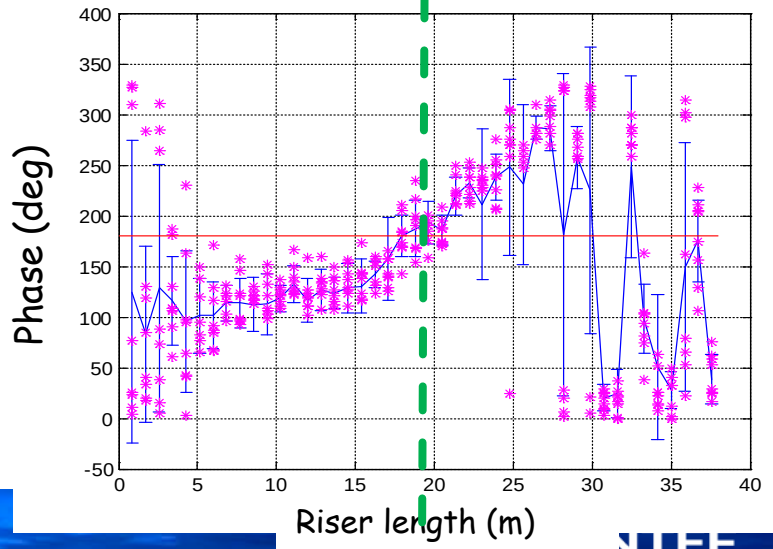
- Zigzag phase variation + drift
- Positive Ce for phase < 180 deg (excitation region)
- Consistent with DNS simulation (Bourguet et al, 2011)
- Wu et al, OMAE2014-24559



Application – IL and CF Interaction







- No zigzag variation due to stronger travelling waves
- Positive Ce for phase < 180 deg (excitation region)

Conclusions

- Inverse analysis method is a valuable tool to obtain hydrodynamic forces/coefficients from VIV experiments with flexible cylinders

- The identified hydrodynamic forces/coefficients can be used to improve existing load models

- Phase between IL and CF displacements is a key parameter to understand the interaction and it is strongly coupled with force coefficients

Thank You!

Reference

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