Summer School
Fluid Dynamics of Sustainability and the Environment
Ecole Polytechnique (Paris), 1-12 July 2019

Fluid-structure interactions
Energy harvesting from flow-induced instabilities

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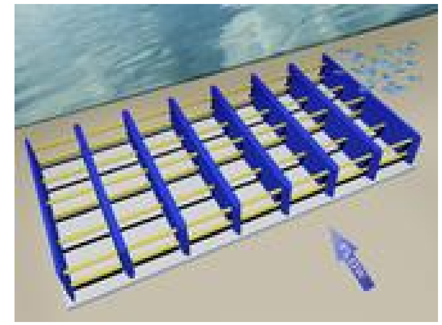
Energy harvesting from flow-induced vibrations

Vortex Induced Vibrations (VIV)



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Flapping wings

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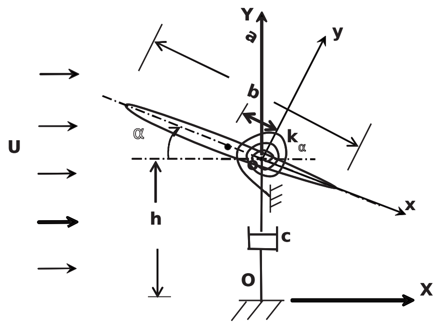
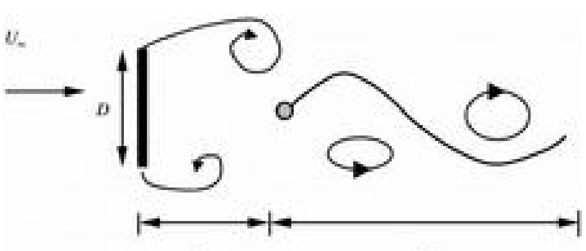
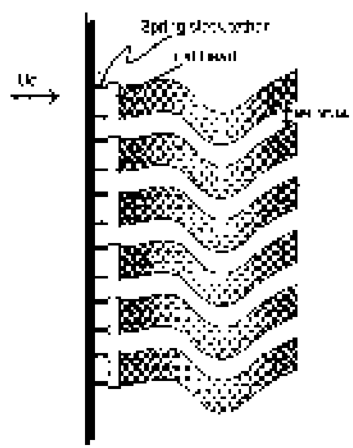


Peng & Zhu, Phys. Fluids, 2009

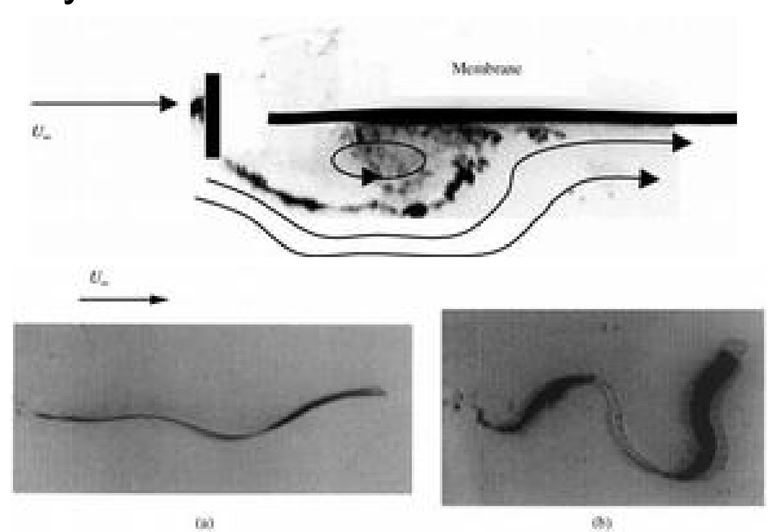
Vibrations of slender structures in instationnary flows



Alen & Smnith, JFS 2002



Techet et al., ISOPE 2002



Alen & Smith, JFS 2002

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Some commercial products

The STINGRAY project (Engineering Business Ltd.)

- Experimental project of the early 2000's
- 15m span 3m chord, displacement amplitude of 12m
- Displacement of the wing transmitted to an hydraulic motor through hydraulic cylinders
- Abandonned project because of economic viability

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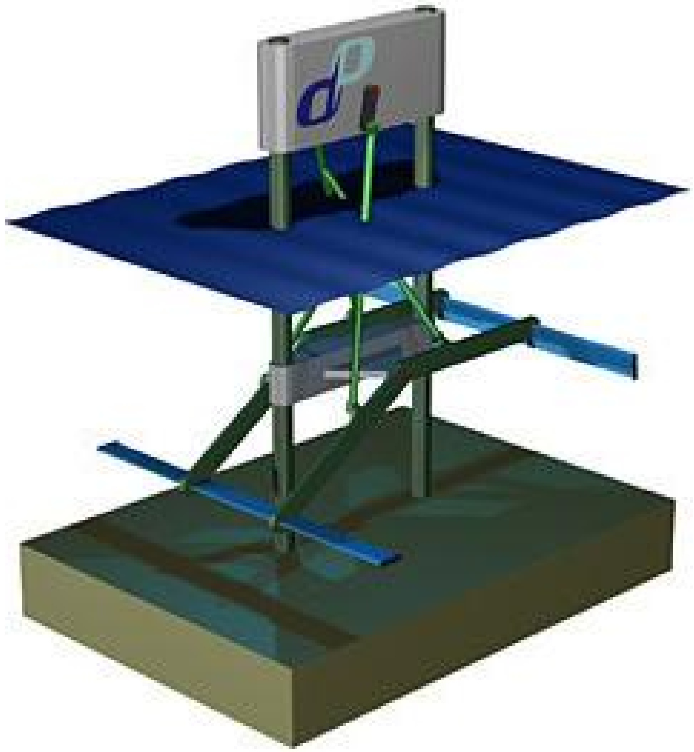
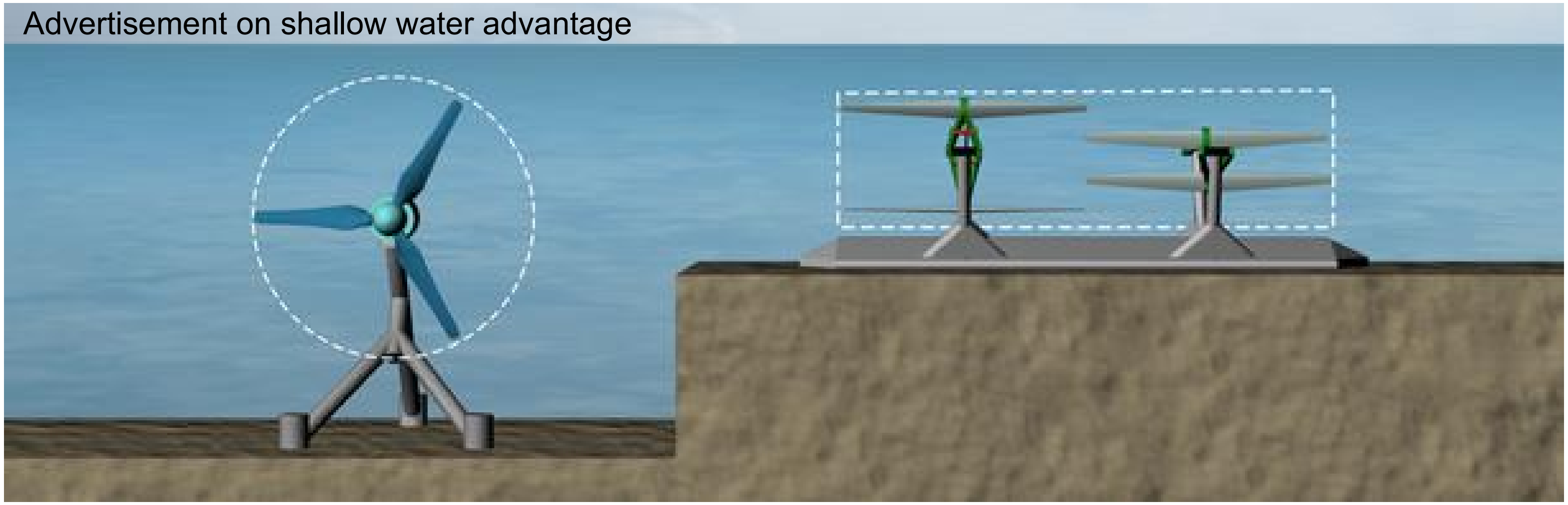
Some commercial products



Pulse Generation

PULSE-TIDAL

- Two wings are phase-locked, translation and rotation of each wing also phase-locked
- Movement transitted to a generator through arms
- Generator can be put in or out the water
- Small vertical space



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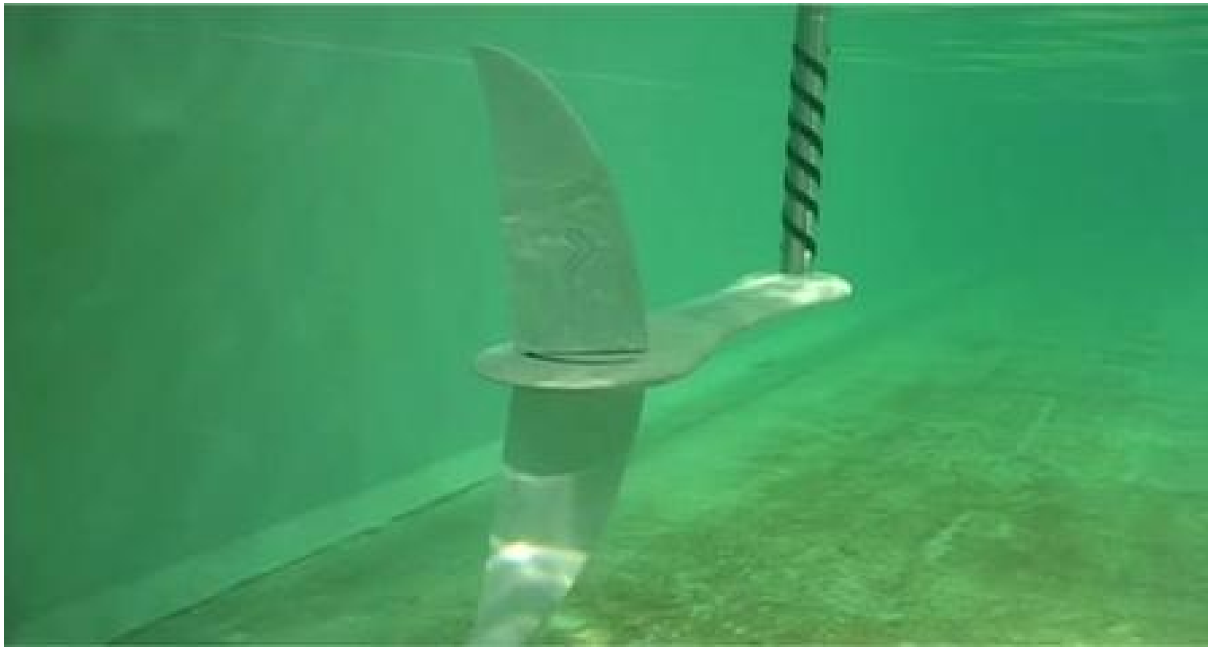

http://www.biopowersystems.com/biostream.html

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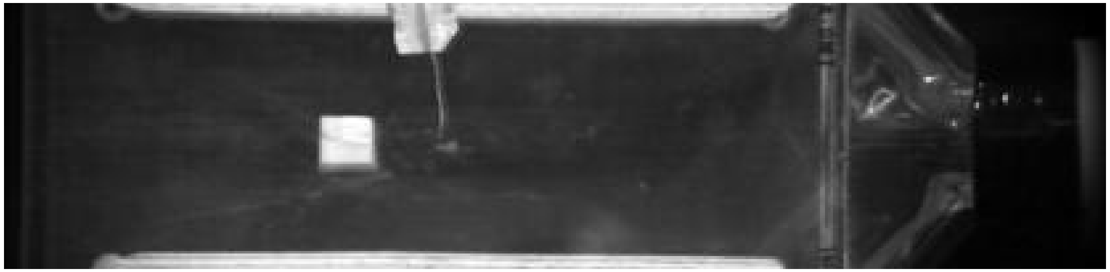
Marine Renewable Energy Laboratory
University of Michigan
A first shot at the multi cylinder VIVACE Converter
V=1.3m/sec=2.6knots; January 31, 2010

www.eel-energy.fr

Flow induced instabilities

Cross-flow instabilities



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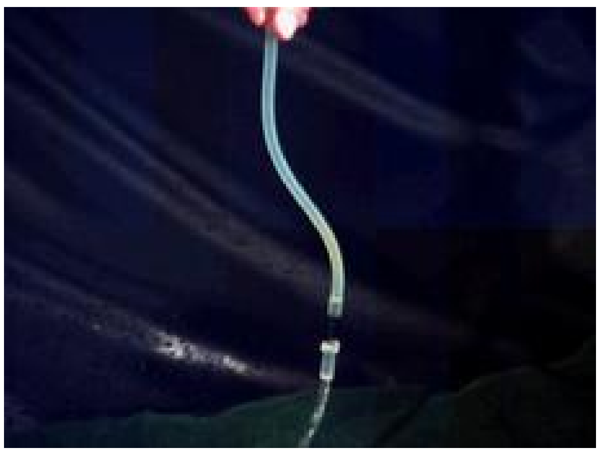
Axial flow instabilities

Fluttering flag



Fluttering pipe

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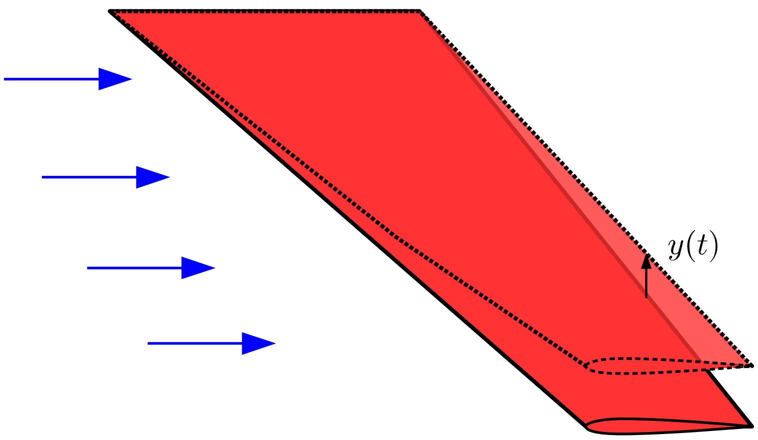
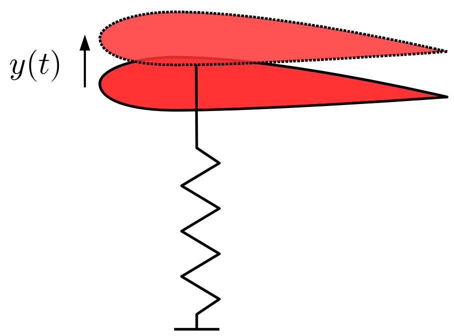
- Objective : Overview of the different physical phenomena that may induce structural vibrations

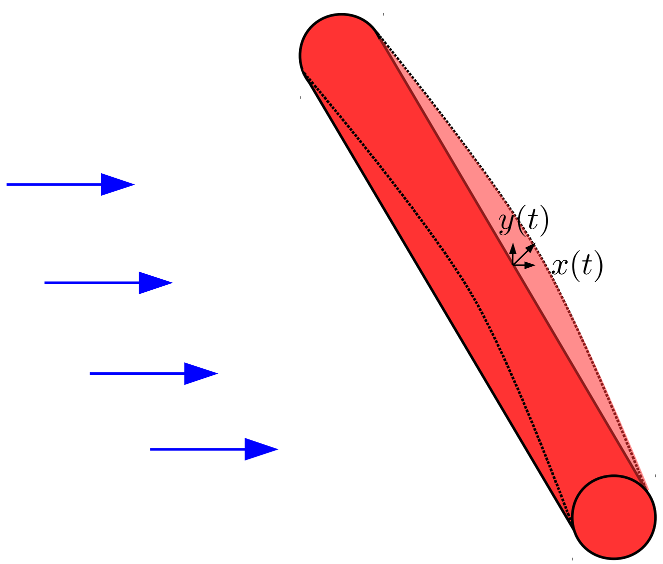
- Part I : Cross-flow instabilities
- Part II : Axial flow instabilities



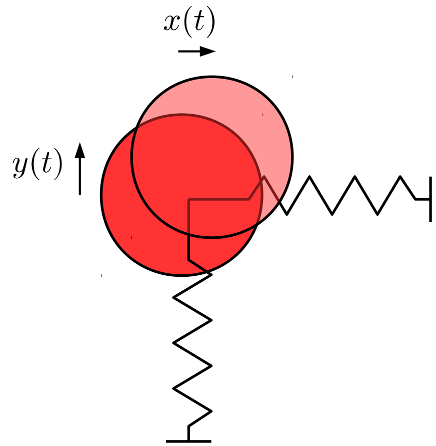
Flexural deformation of a wing



Translation of an airfoil profile + one stiffness

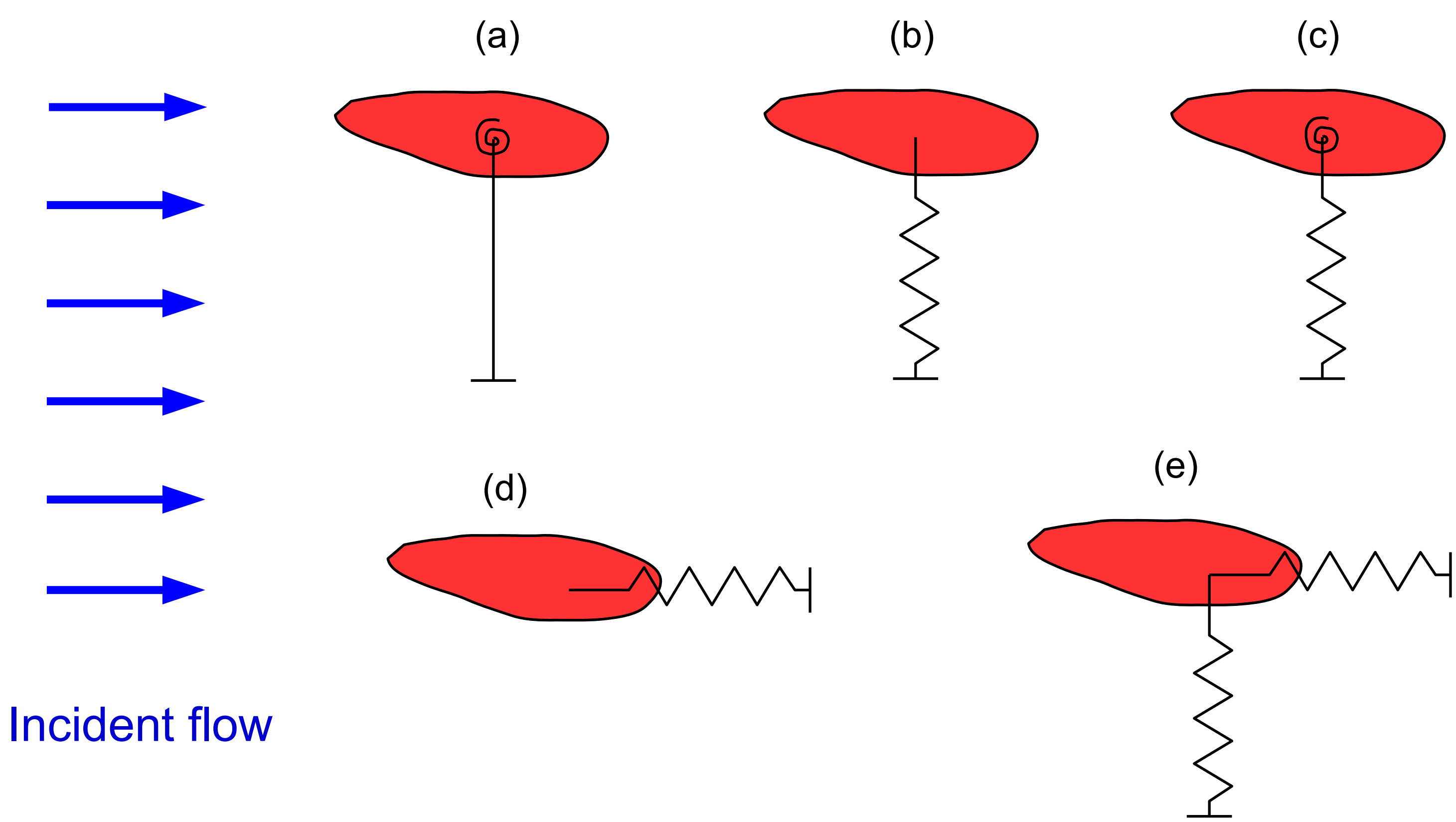


Two polarities flexural deformation of a cylinder

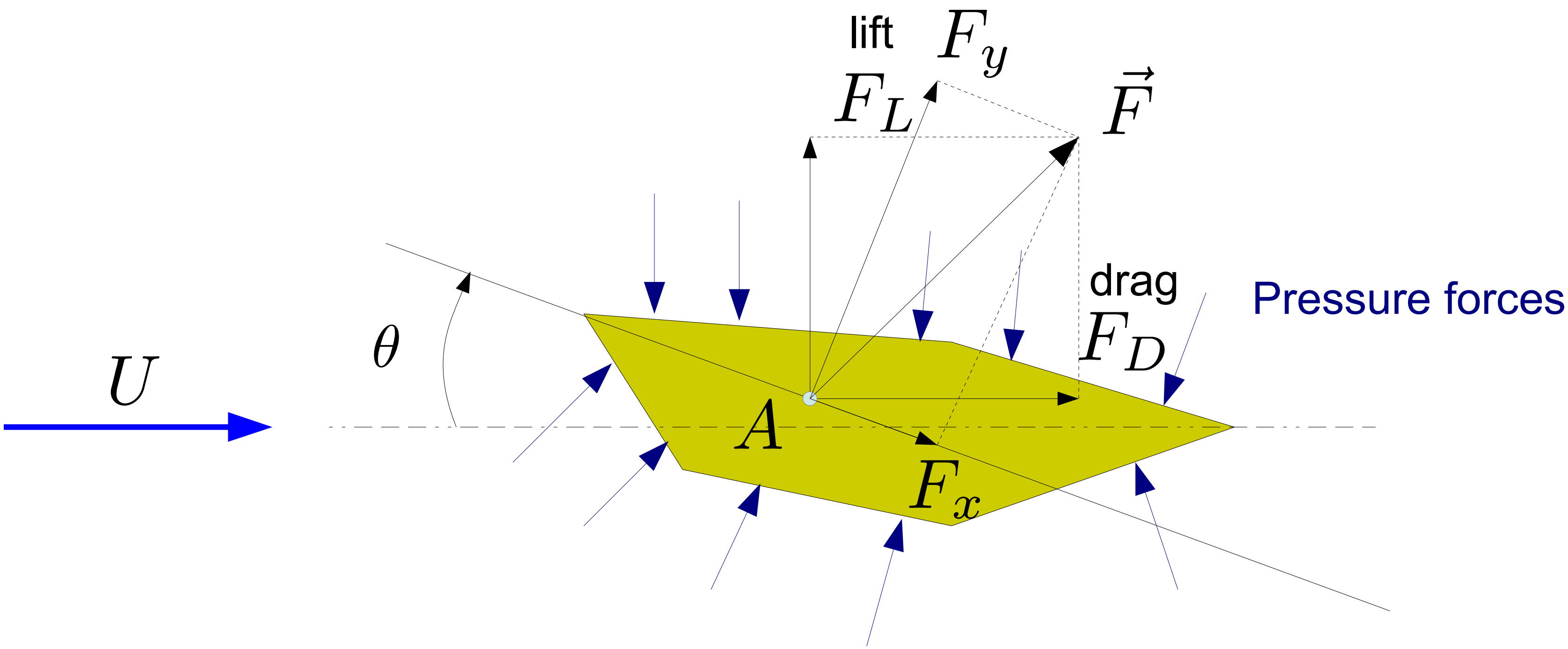


Translation of a circular section + two stiffnesses

Cases considered here



Aerodynamic efforts acting on a solid (2D)



- Forces per unit length
- Definition of non-dimensional coefficients :

$$C_L = \frac{F_L}{\frac{1}{2}\rho U^2 L} \qquad C_D = \frac{F_D}{\frac{1}{2}\rho U^2 L} \qquad C_x = \frac{F_x}{\frac{1}{2}\rho U^2 L} \qquad C_y = \frac{F_y}{\frac{1}{2}\rho U^2 L}$$

- Coefficients function of the Reynolds number and θ

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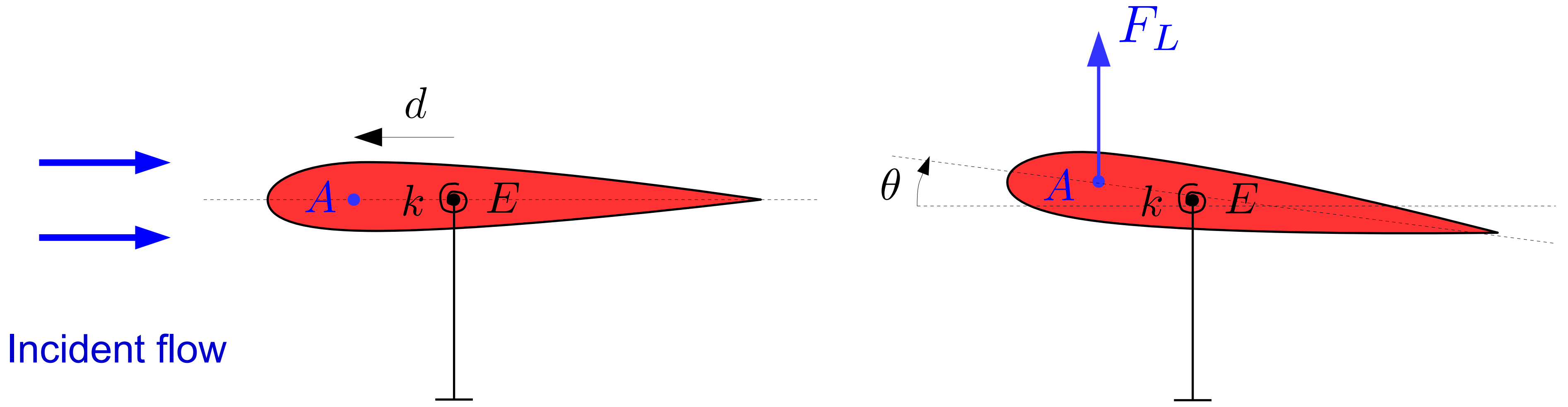
Buckling instability due to negative flow-induced stiffness

Buckling instability due to negative flow-induced stiffness



- Lift force : $F_L = \frac{1}{2}\rho U^2 S C_L$ with $C_L = C_L(\theta, R_e)$

- Small angles of attack : $C_L \sim \theta \frac{\partial C_L}{\partial \theta} = \theta C'_L$

$$M = dF_L$$

- Angle of attack governed by : $J\ddot{\theta} + \left[k - \frac{1}{2}\rho U^2 S d C'_L\right]\theta = 0$

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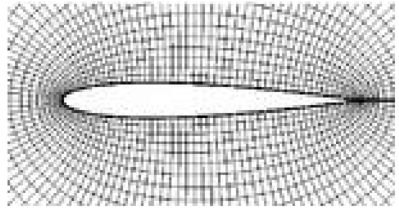
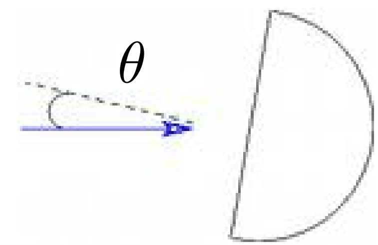
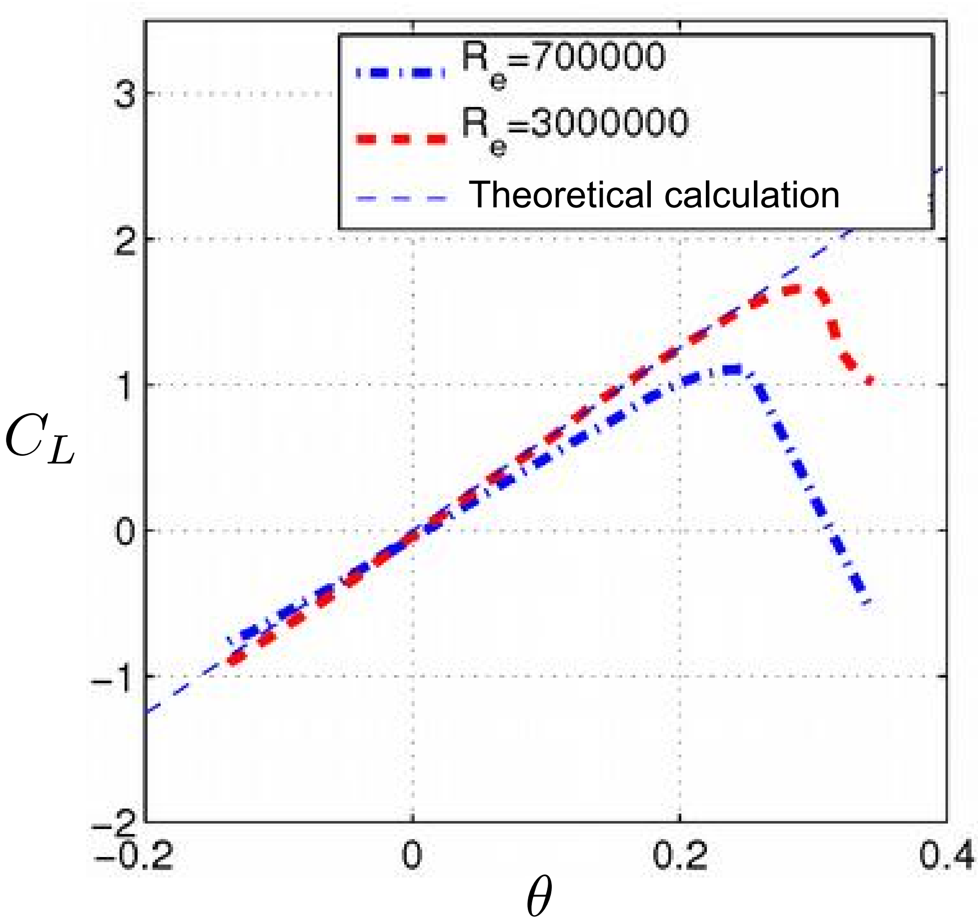
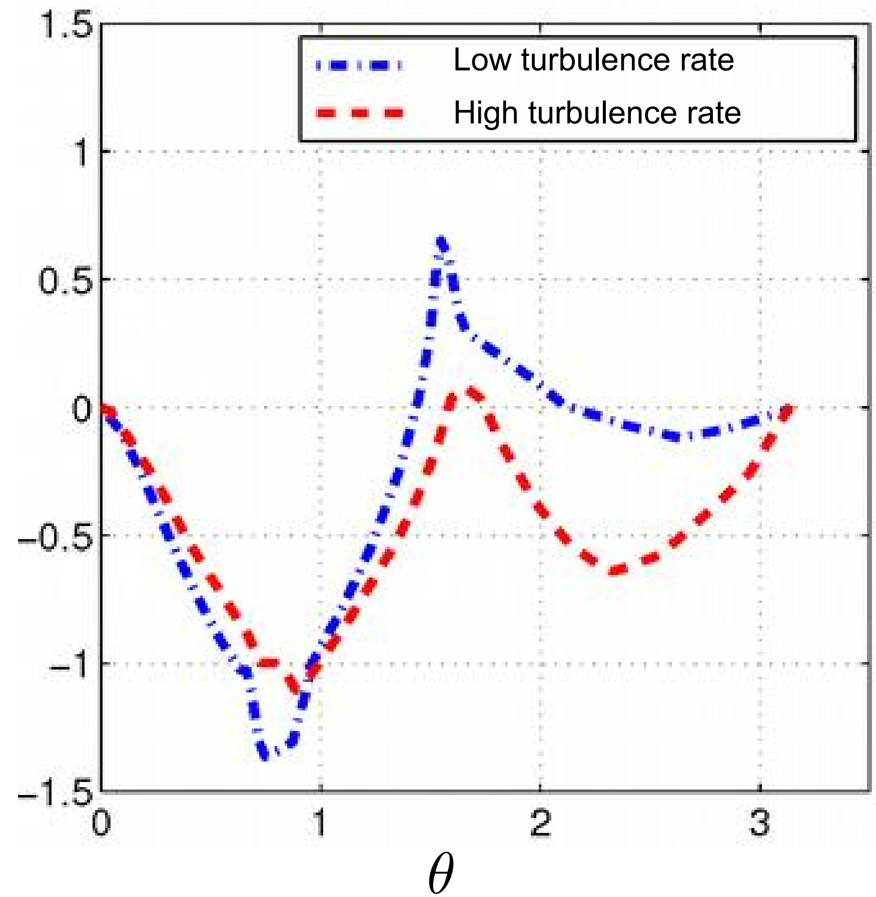
NACA0012




θ


R_e=700000
R_e=3000000
Theoretical calculation
3
2
1
0
−1
−2
−0.2
0
0.2
0.4
C_L
θ


Low turbulence rate
High turbulence rate
1.5
1
0.5
0
−0.5
−1
−1.5
0
1
2
3
θ

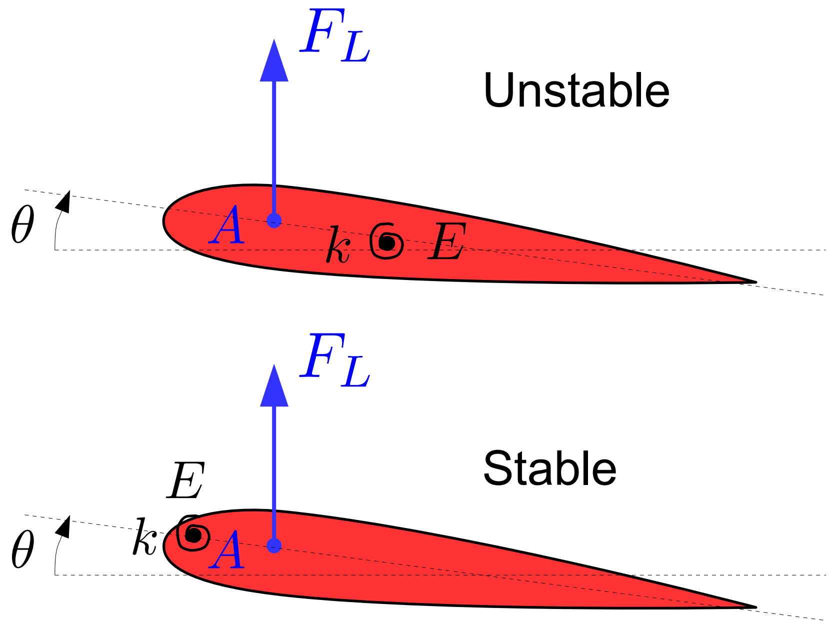
Buckling instability due to negative flow-induced stiffness

$$J\ddot{\theta} + \left[k - \frac{1}{2}\rho U^2 S d C_L'\right]\theta = 0$$

- Negative stiffness if : $U > \sqrt{\dfrac{2k}{\rho S d C_L'}}$

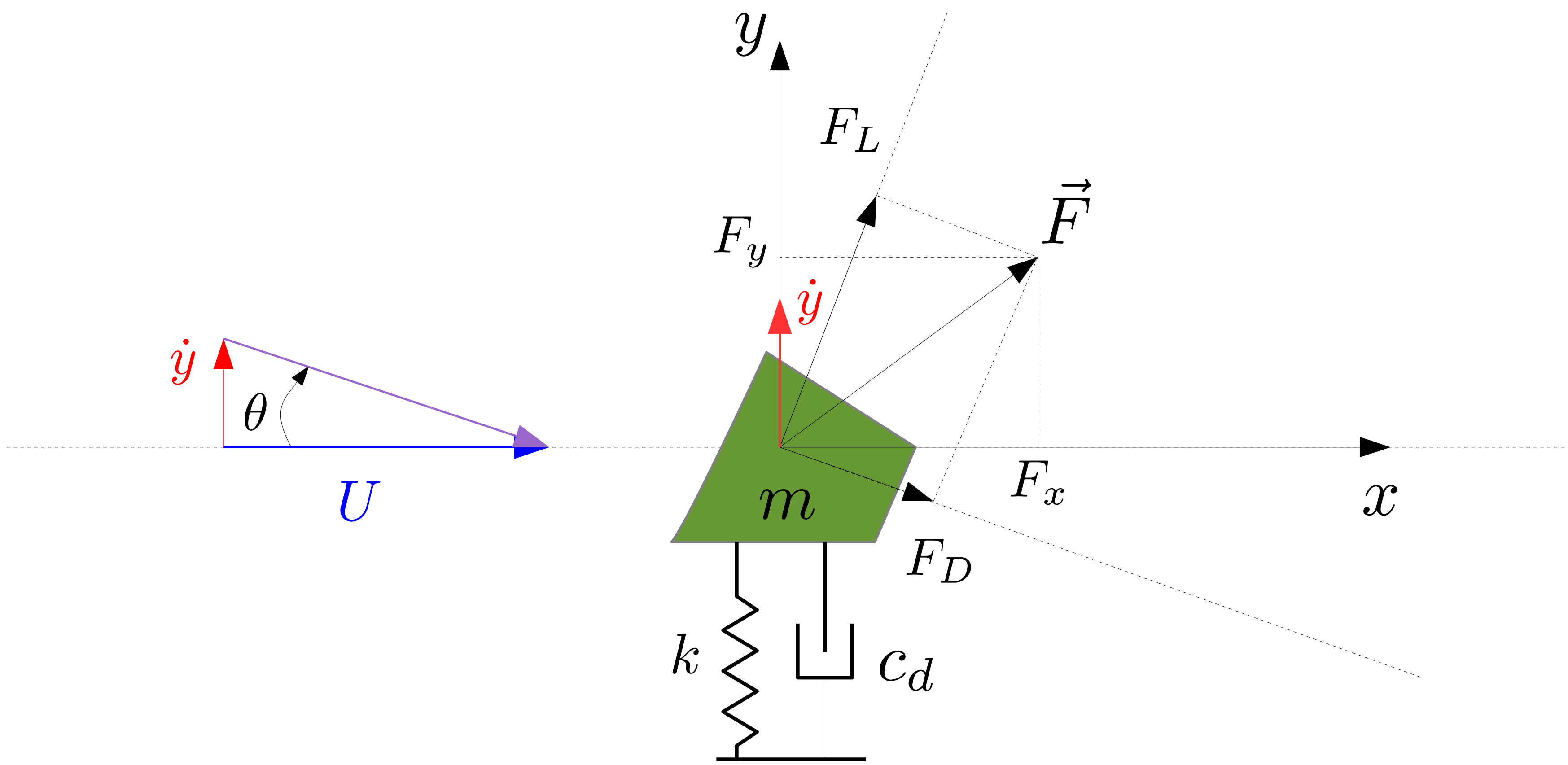
  → (buckling instability)

Weathercock



Dynamic instability by negative flow-induced damping

Added damping force



Instability criterion

$$F_y \sim -\frac{1}{2}\rho U^2 S \frac{\dot{y}}{U}\left(C_L' + C_D\right)$$

$$U > -\frac{2c_d}{\rho U S (C_L' + C_D)}$$

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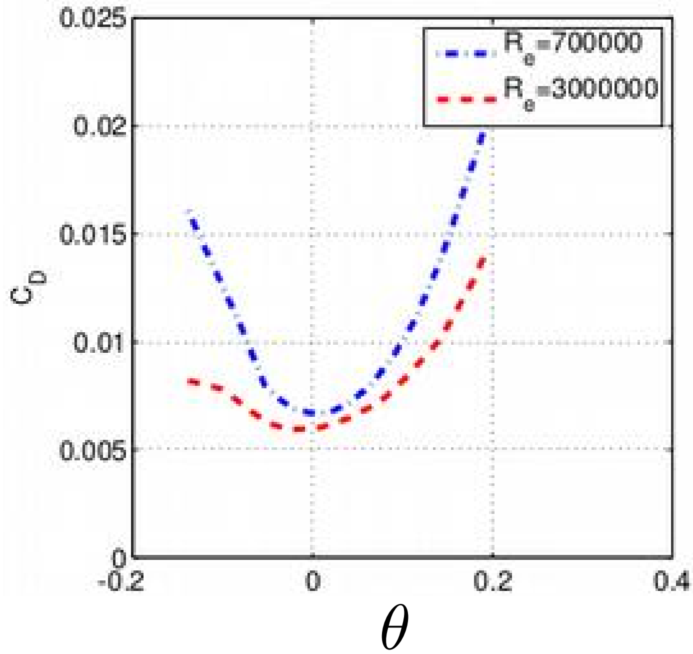
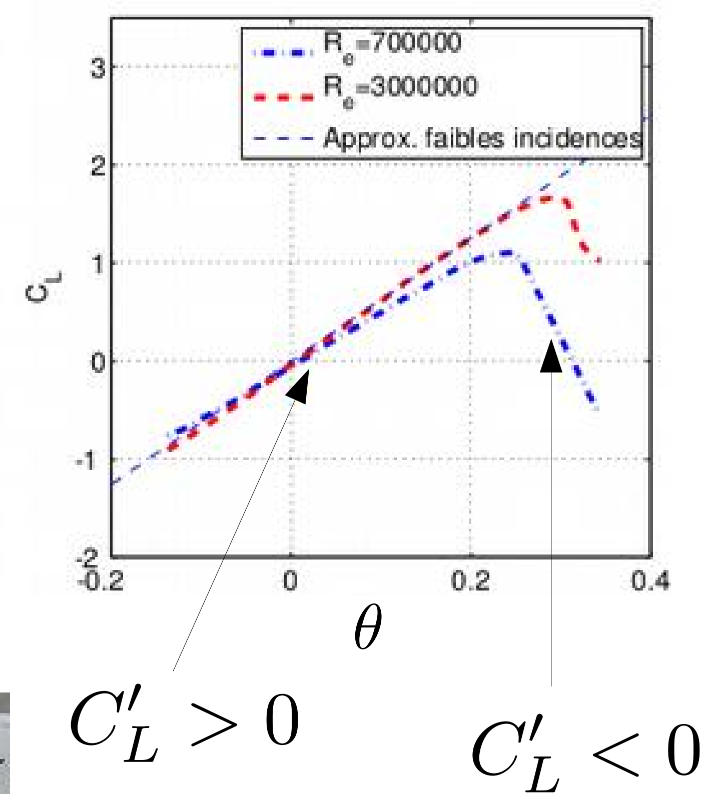
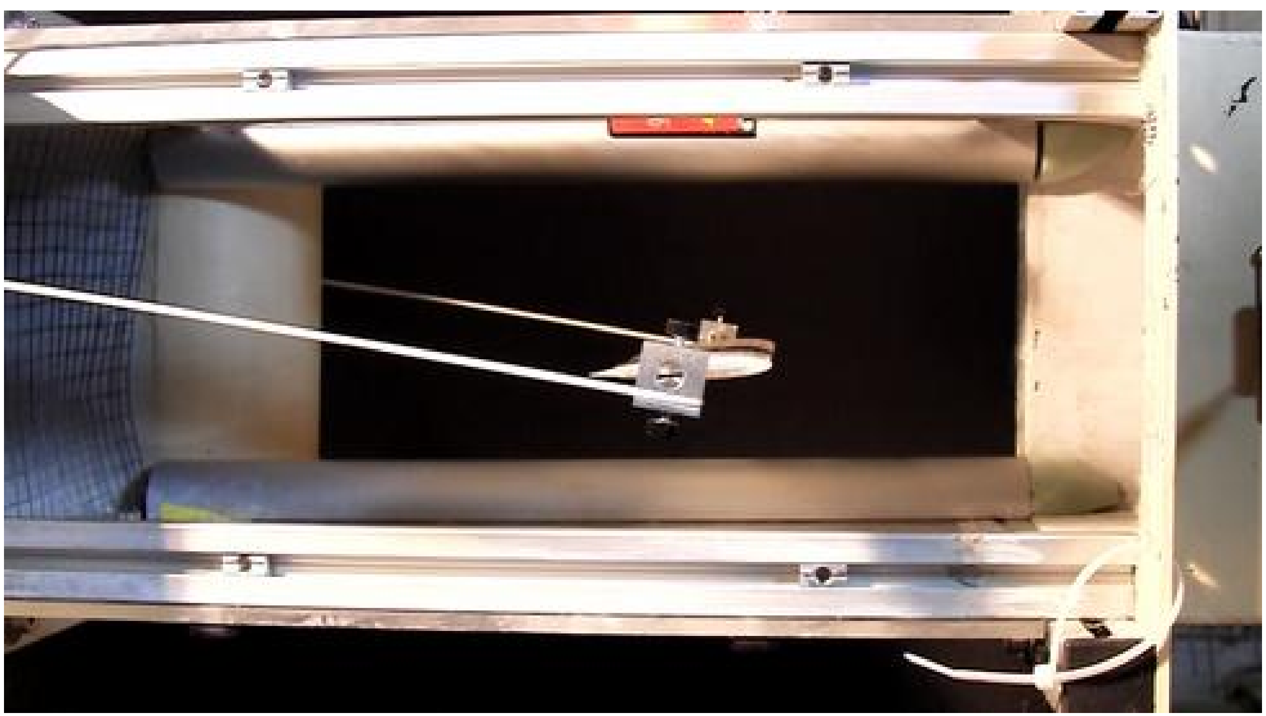
NACA 0012 airfoil







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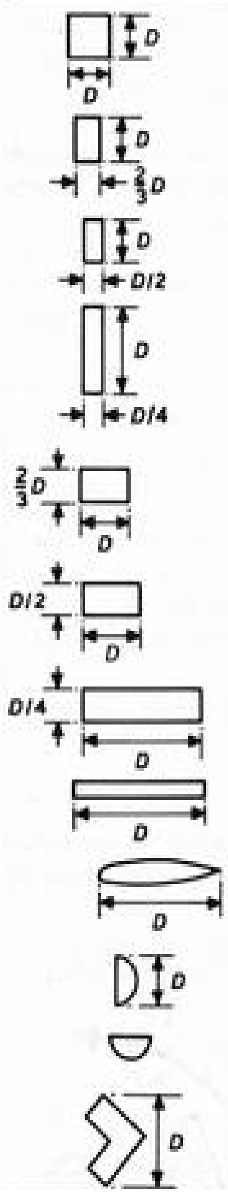
Other sections

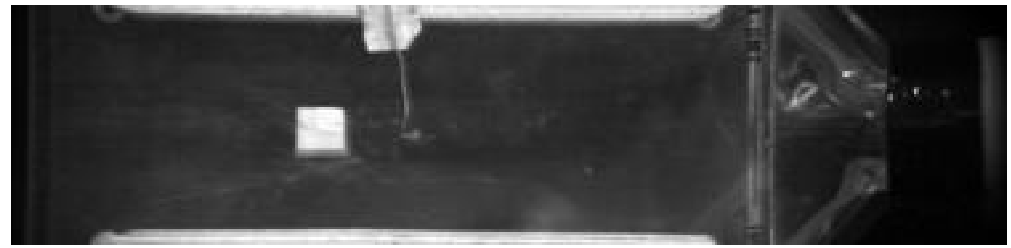
$$-\frac{\partial C_L}{\partial \theta}$$



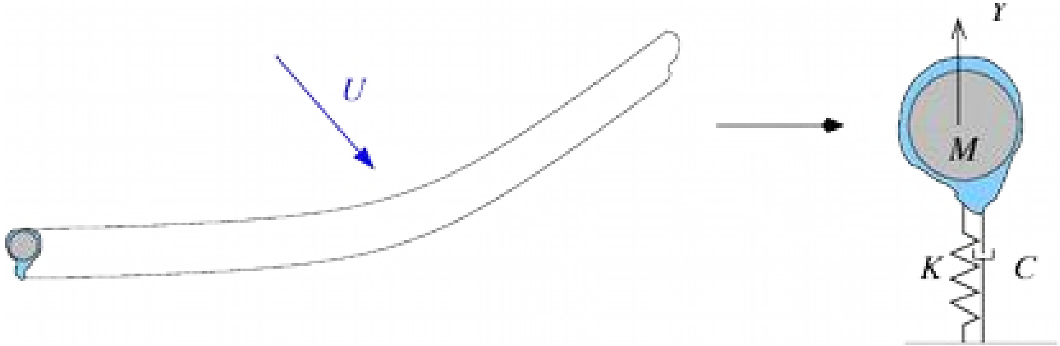
Section	Smooth flow	Turbulent flow[b]	Reynolds number
D, D	3.0	3.5	10^5
D, $\frac{2}{3}D$	0.	−0.7	10^5
D, D/2	−0.5	0.2	10^5
D, D/4	−0.15	0.	10^5
$\frac{2}{3}D$, D	1.3	1.2	66 000
D/2, D	2.8	−2.0	33 000
D/4, D	−10.	—	2 000–20 000
D	−6.3	−6.3	$>10^3$
D	−6.3	−6.3	$>10^3$
D	−0.1	0.	66 000
	−0.5	2.9	51 000
D	0.66	—	75 000

(Blevins, 1990)

Case of the square



Ice on cables



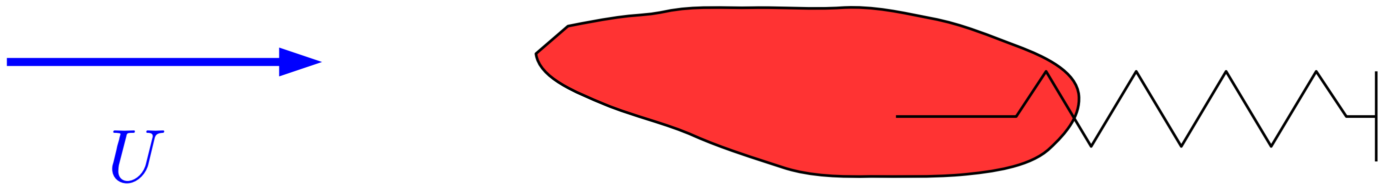
telegraph.co.uk

icefree.ro

edn.com

Drag crisis instability

Oscillations in the direction of the flow



$$F_D = -\frac{1}{2}\rho U^2 S \left(C_D(R_E) + 2\frac{\dot{x}}{U} C_D(R_E) + \frac{\dot{x}}{U} R_E \frac{\partial C_D}{\partial R_E} \right)$$

Instability if

$$2C_D(R_E) + R_E \frac{\partial C_D}{\partial R_E} < 0$$

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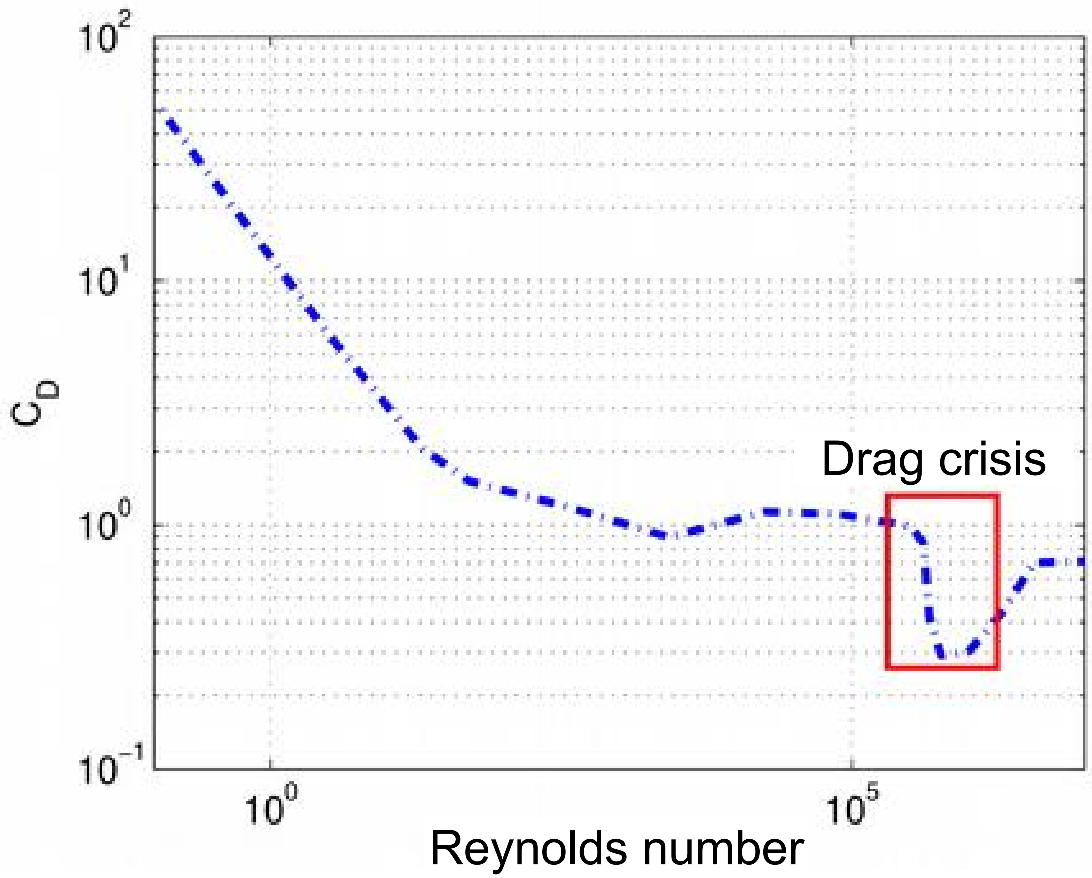
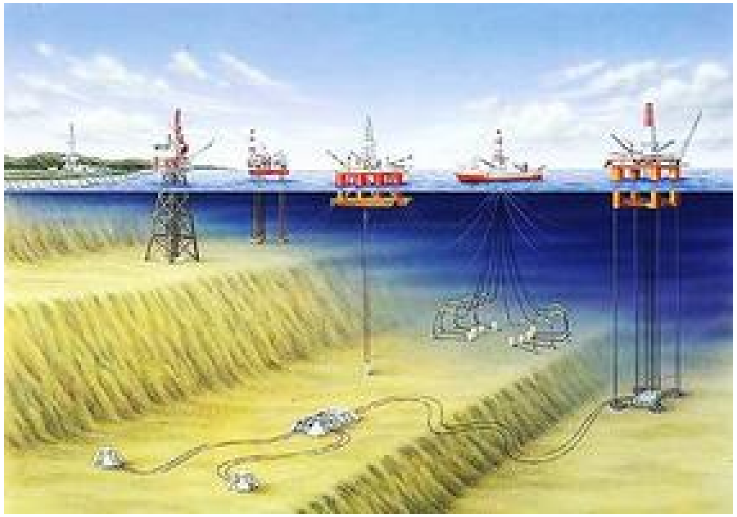
Case of the circular section



Common problem
in the offshore industry



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Coupled mode flutter

How to explain wing flutter ?

$$-\frac{\partial C_L}{\partial \theta}$$

Section	Smooth flow	Turbulent flow[a]	Reynolds number
D, D	3.0	3.5	10^5
D, 2/3 D	0.	−0.7	10^5
D, D/2	−0.5	0.2	10^5
D, D/4	−0.15	0.	10^5
2/3 D, D	1.3	1.2	66 000
D/2, D	2.8	−2.0	33 000
D/4, D	−10.	—	2 000–20 000
D	−6.3	−6.3	$>10^3$
D	−6.3	−6.3	$>10^3$
D	−0.1	0.	66 000
	−0.5	2.9	51 000
D	0.66	—	75 000

(Blevins, 1990)

Thin profiles are stable with respect to galloping

But ...

Observation : the instability mechanism should involve flexural and torsional deformations.

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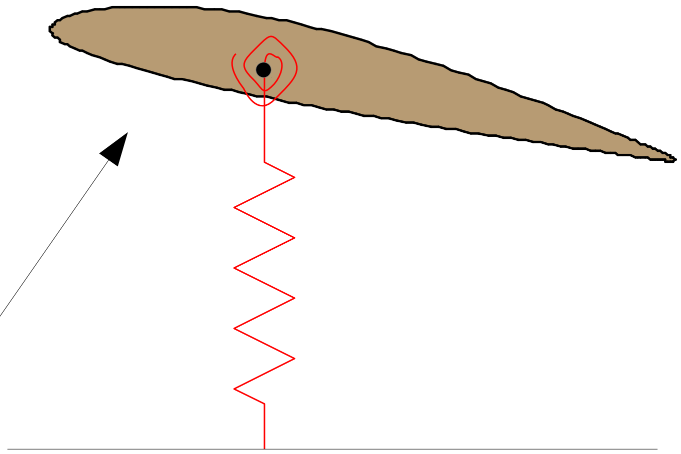
Example : flutter of a wing profile

Coupled torsional and flexural modes of an airfoil

Equivalent 2D profile in translation and rotation



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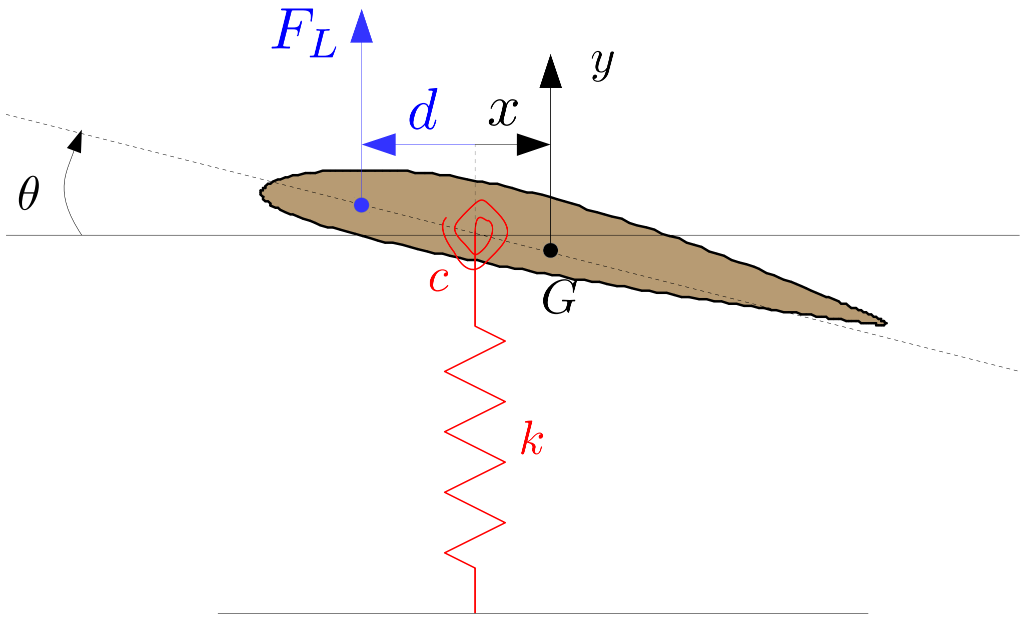

G center of gravity

m mass

J moment of inertia

If G is not at the elastic center, coupled flexural and torsional modes :

$$m\ddot{y} + ky + kx\theta = 0$$

$$J\ddot{\theta} + (c + kx^2)\theta + kxy = 0$$

With an incident flow :

$$\begin{bmatrix} m & 0 \\ 0 & J \end{bmatrix} \begin{bmatrix} \ddot{y} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} k & kx - \frac{1}{2}\rho U^2 S C_L' \\ kx & c + kx^2 - \frac{1}{2}\rho U^2 S(x+d) C_L' \end{bmatrix} \begin{bmatrix} y \\ \theta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

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Eigenfrequencies and phase difference between eigenmodes components

$$\begin{bmatrix} m & 0 \\ 0 & J \end{bmatrix} \begin{bmatrix} \ddot{y} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} k & kx - \frac{1}{2}\rho U^2 S C_L' \\ kx & c + kx^2 - \frac{1}{2}\rho U^2 S (x+d) C_L' \end{bmatrix} \begin{bmatrix} y \\ \theta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Dynamical equation of the form :

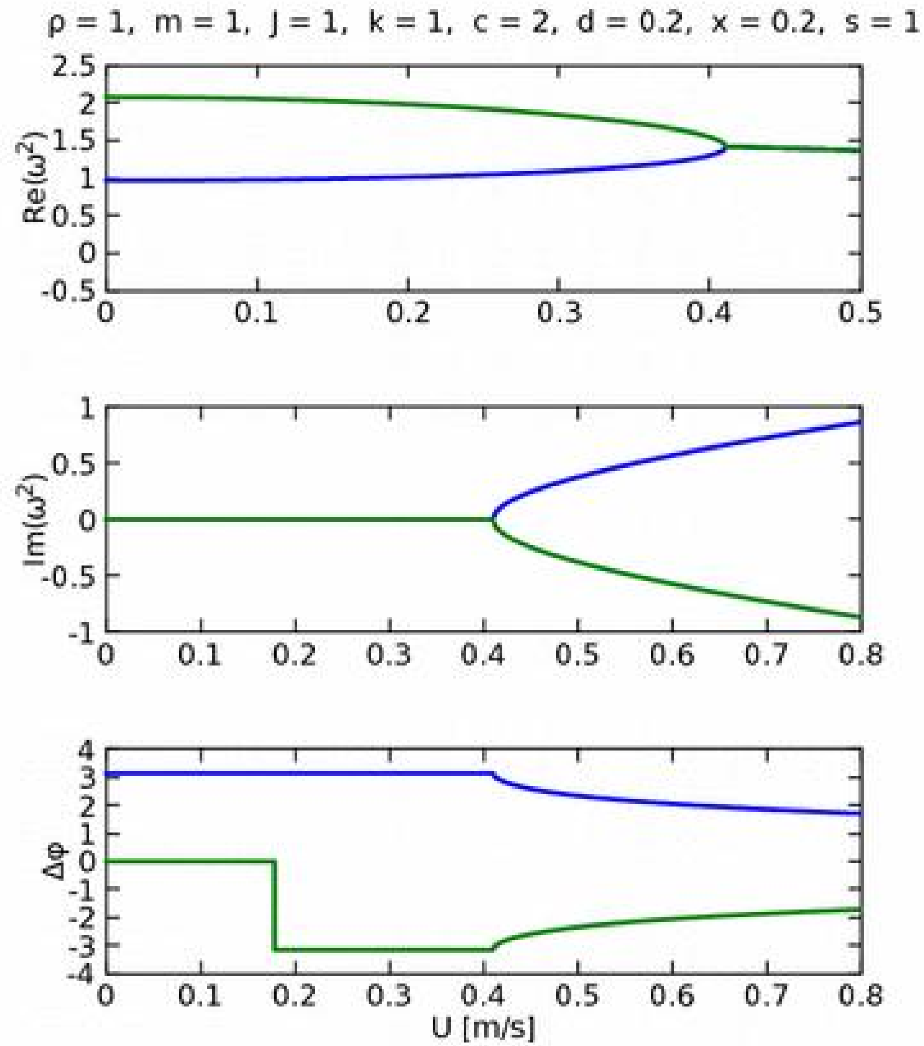
$$M\ddot{\vec{q}} + K\vec{q} = 0$$

Solutions sought in the form :

$$\vec{q} = \vec{q}_0 \mathrm{e}^{\mathrm{i}\omega t} = \vec{q}_0 \mathrm{e}^{-\omega_i t} \mathrm{e}^{\mathrm{i}\omega_r t}$$

Eigenvalue problem :

$$M^{-1}K\vec{q}_0 = \omega^2 \vec{q}_0$$



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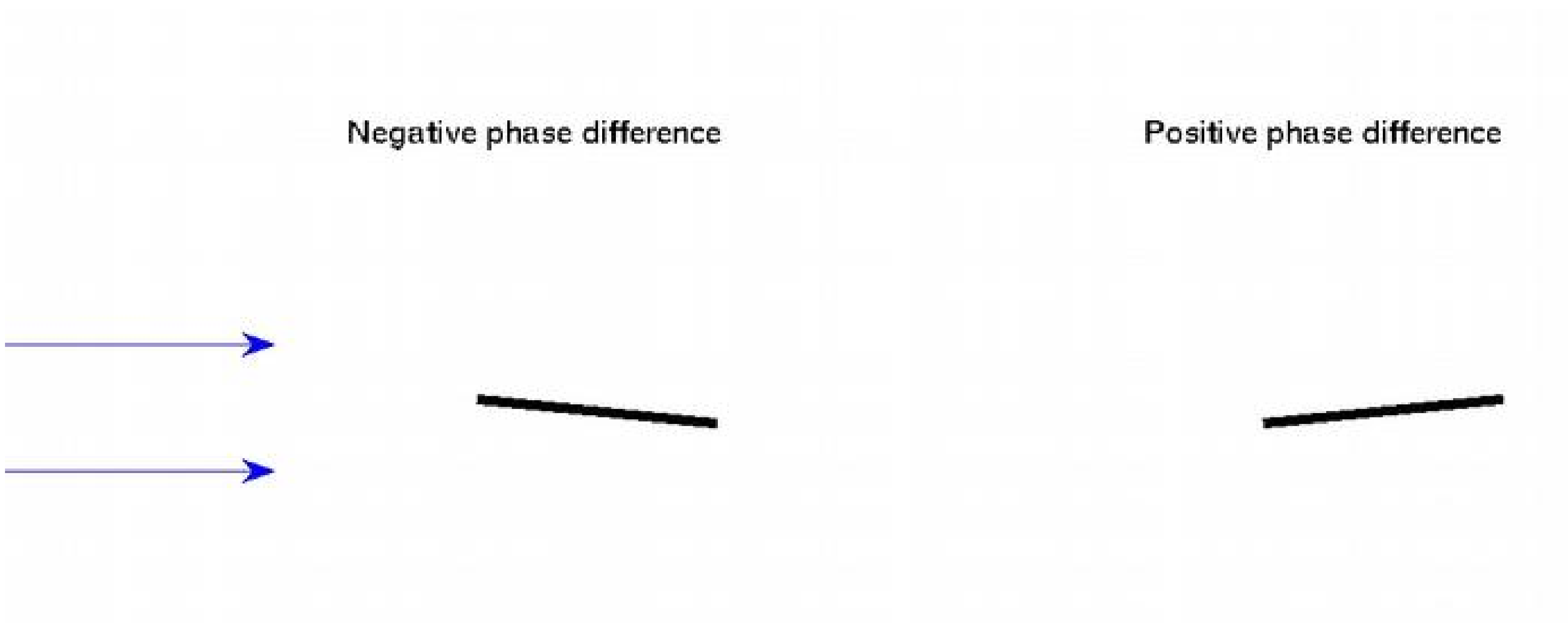
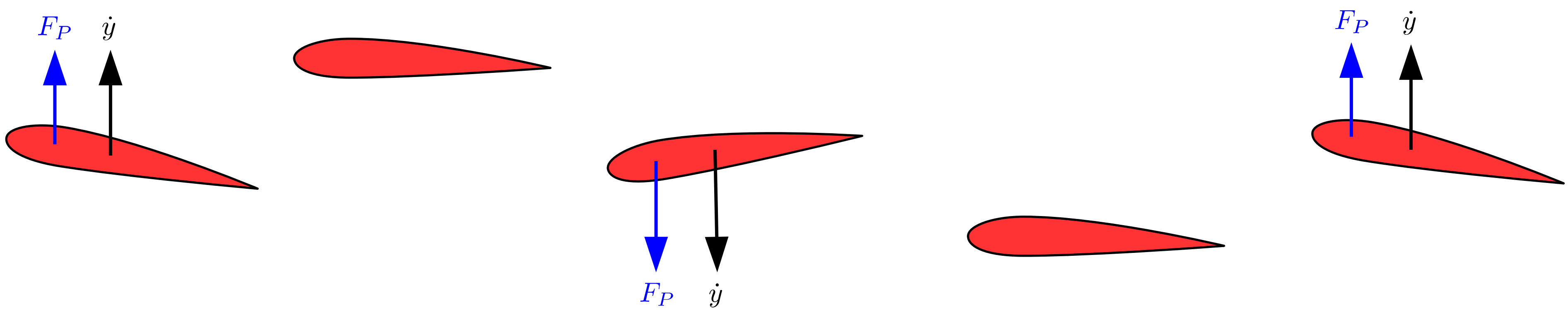
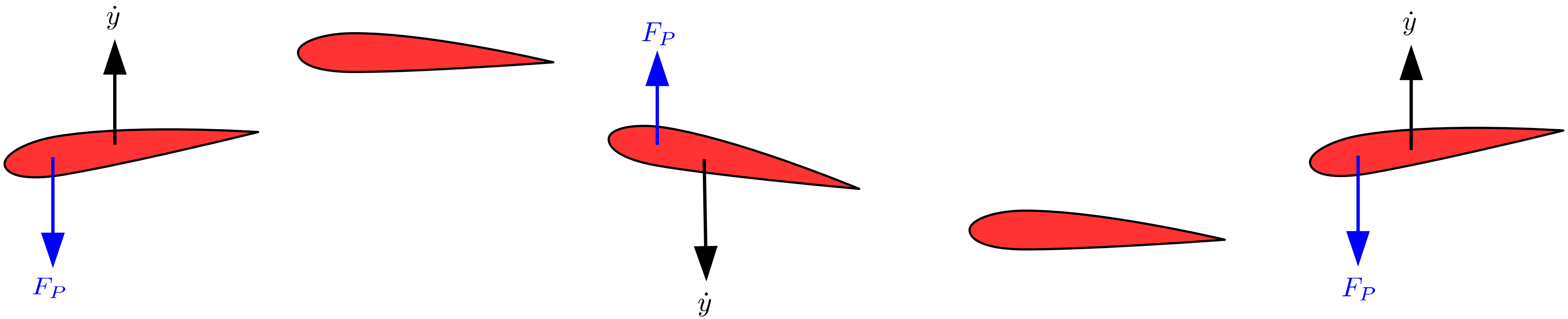

Negative phase difference
Positive phase difference

Unstable mode : positive work



Stable mode : negative work



Work depends on the path : non-conservative force...

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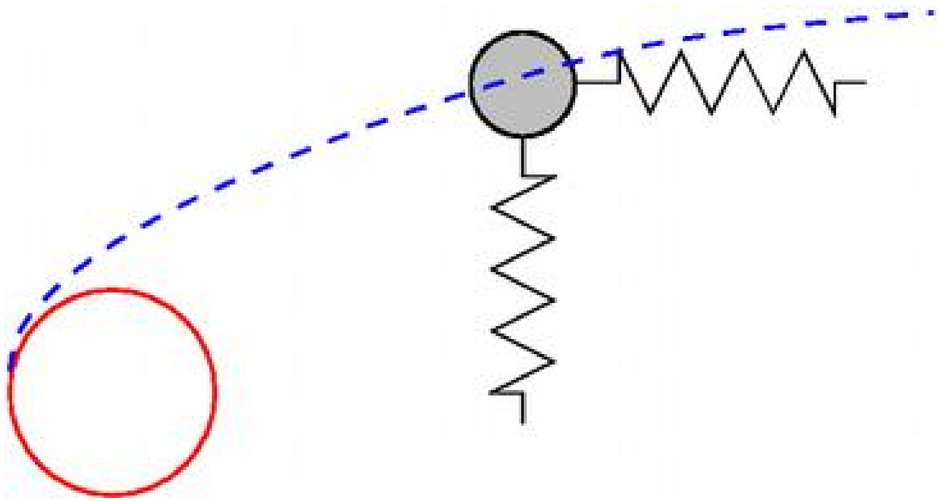
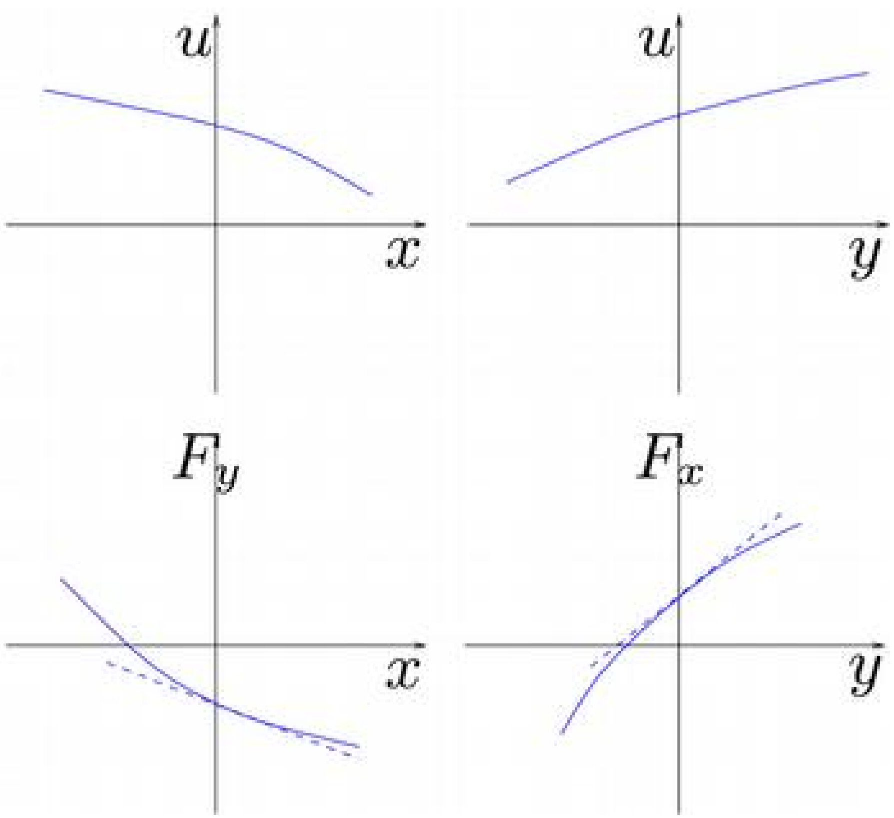
Coupled mode flutter of cables

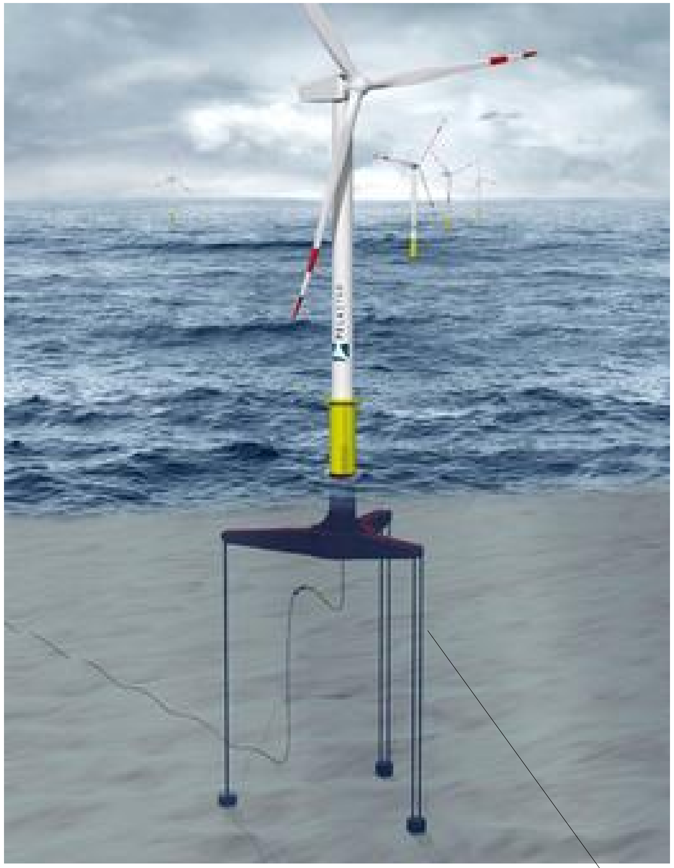


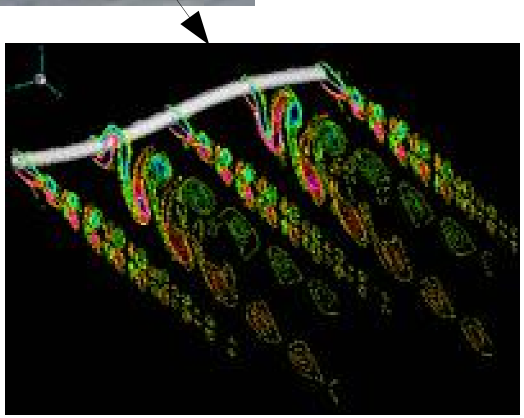


$$
\begin{aligned}
m\ddot{x} + k_x x &= x\frac{\partial F_x}{\partial x} + y\frac{\partial F_x}{\partial y} \\
m\ddot{y} + k_y y &= x\frac{\partial F_y}{\partial x} + y\frac{\partial F_y}{\partial y}
\end{aligned}
$$

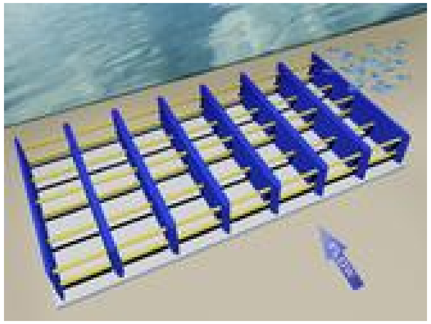
Vortex-induced vibration

Mooring lines in RME





Energy harvesting



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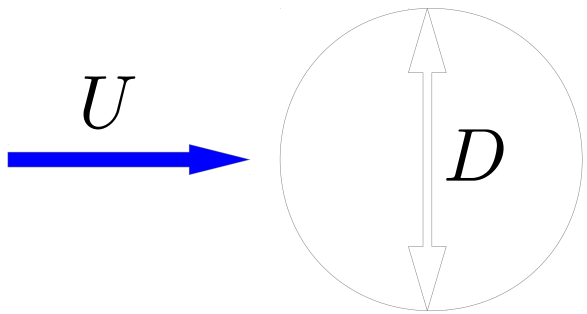
Vortex shedding around a circular cylinder



$$R_e = \frac{UD}{\nu}$$

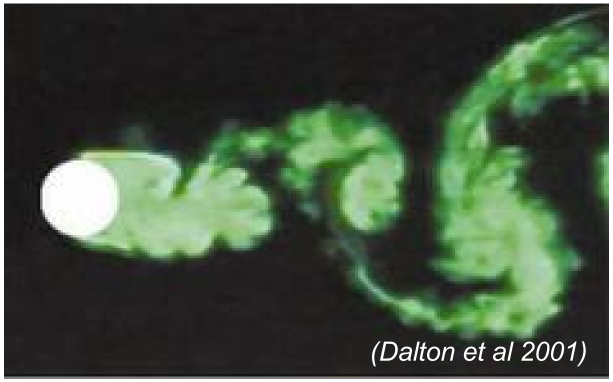
$R_e = 100$

(Dalton et al 2001)

$R_e = 1000$

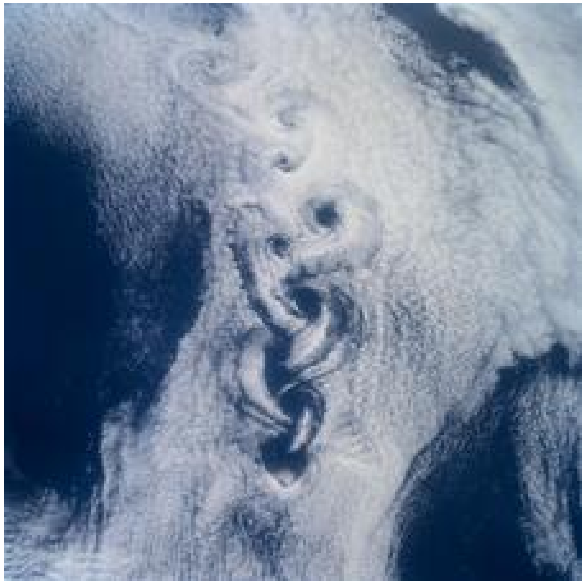
(Dalton et al 2001)

$R_e = 3000$



(Dalton et al 2001)

$R_e = 6 \times 10^9$

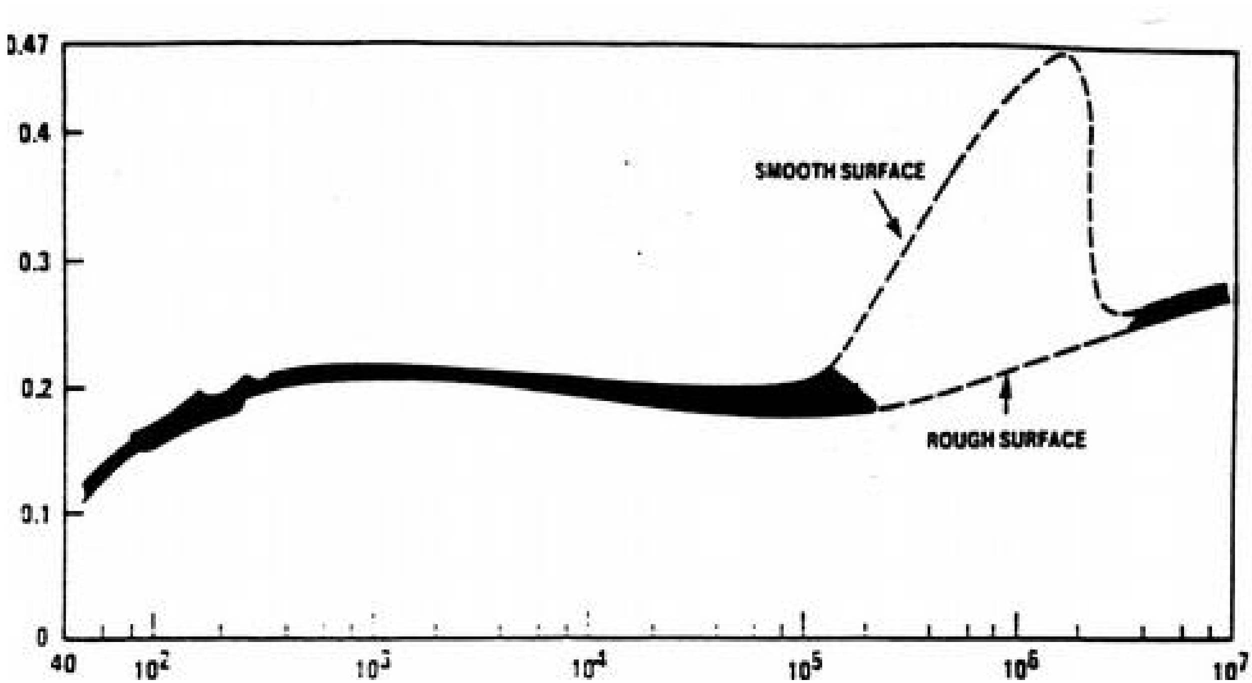


Rishiri island (source wikipedia)

Thiria & Cadot

Frequency of the vortex street behind a cylinder

Strouhal number $S_t = \frac{FD}{U}$



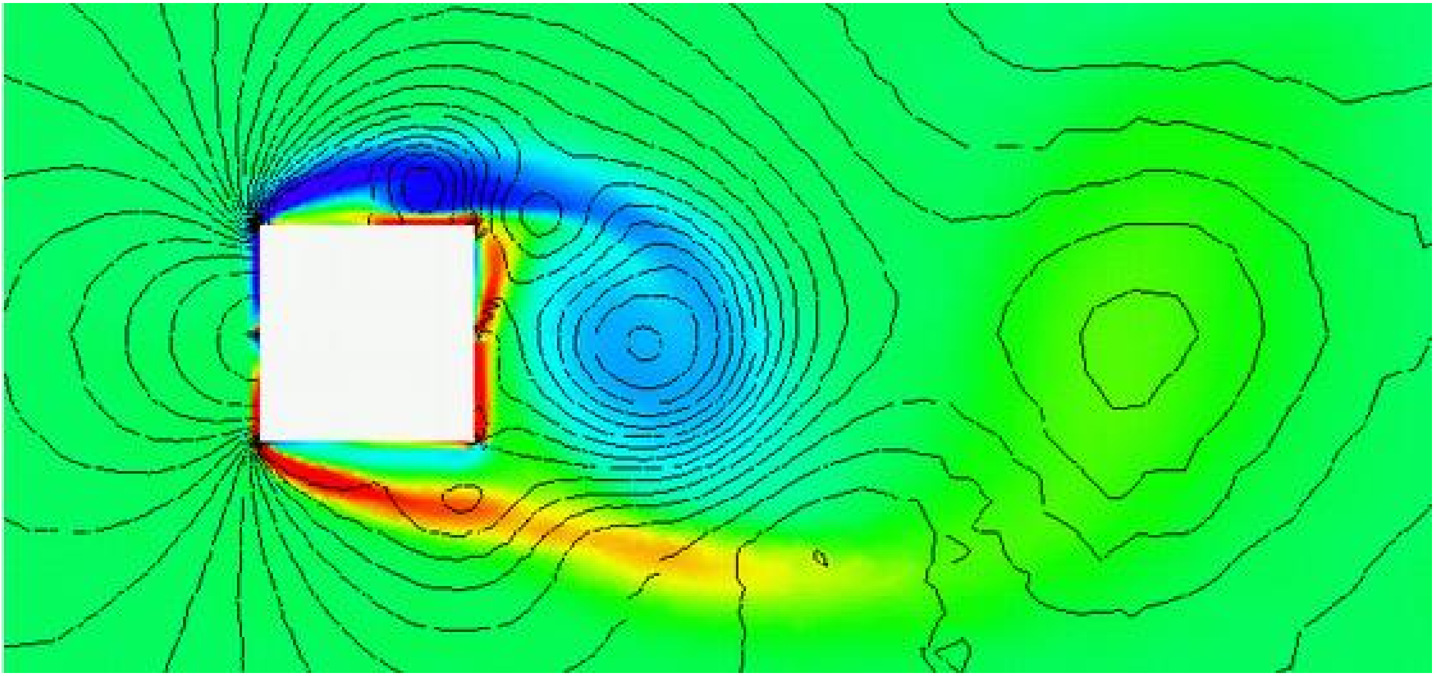
Blevins, 1990

Reynolds number $R_e = \frac{UD}{\nu}$

- Strouhal number almost constant (~0.2, 0.3)
- Frequency of the vortex shedding varies almost linearly with the flow velocity

Other geometries

Square section St ~ 0.16



- Each cross-section has a unique Strouhal number
- Robust, generic, and predictible phenomenon

$$F = \frac{S_t U}{D}$$

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This vortex shedding acts like a fluctuatig force on the structure

Forcing → Vibrating structure → Response ?

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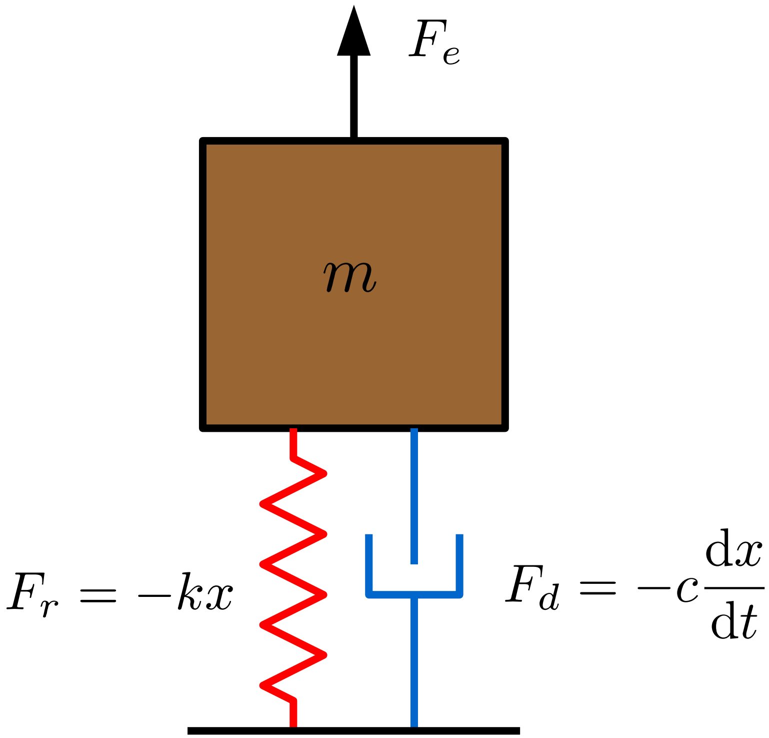
Harmonic oscillator : forced motion



$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + c\frac{\mathrm{d}x}{\mathrm{d}t} + kx = F_e$$

- Harmonic forcing :

$$F_e = \mathrm{Re}(F_0 e^{i\omega t}) \quad F_0 \in \mathbb{C}$$

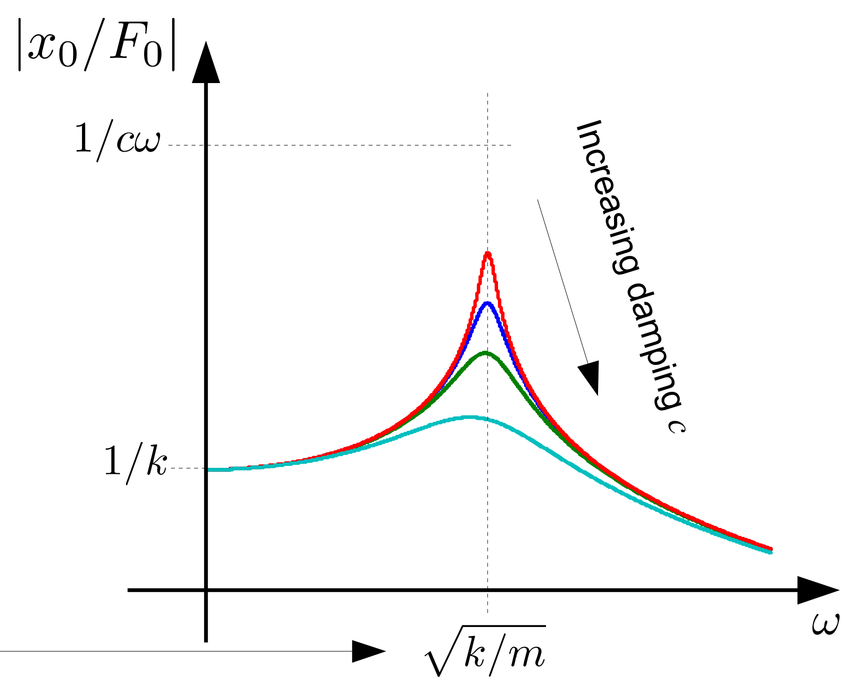
- Hyp. : response at the same frequency :

$$x = \mathrm{Re}(x_0 e^{i\omega t}) \quad x_0 \in \mathbb{C}$$

$$(-\omega^2 m + ic\omega + k)x_0 e^{i\omega t} = F_0 e^{i\omega t}$$

$$\frac{x_0}{F_0} = \frac{1}{m(\frac{k}{m} - \omega^2) + ic\omega}$$

(transfer function)



This is the frequency of free vibrating system

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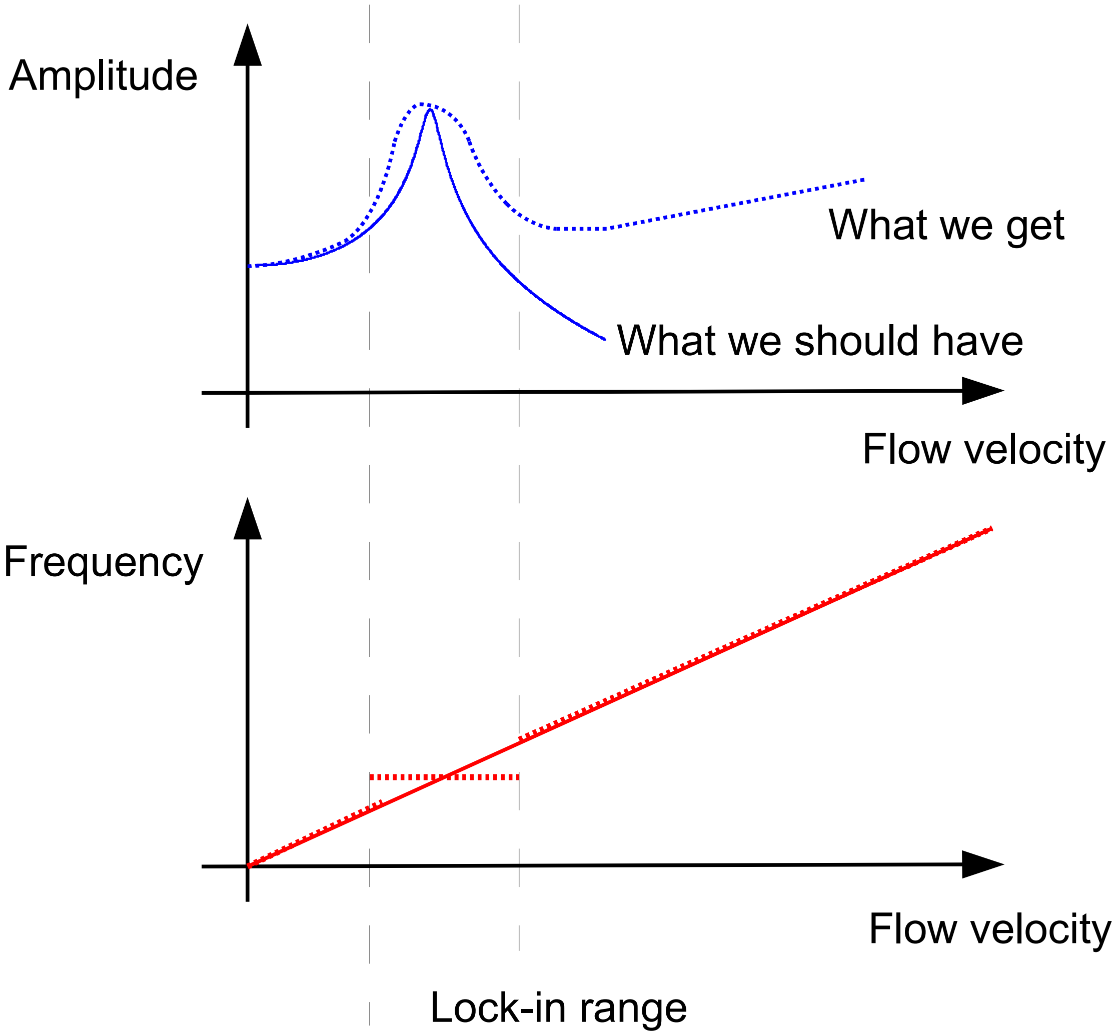
Lock-in phenomenon



In the lock-in range, fluid-structure coupling is improved, frequency is locked to the eigenfrequency of the oscillator

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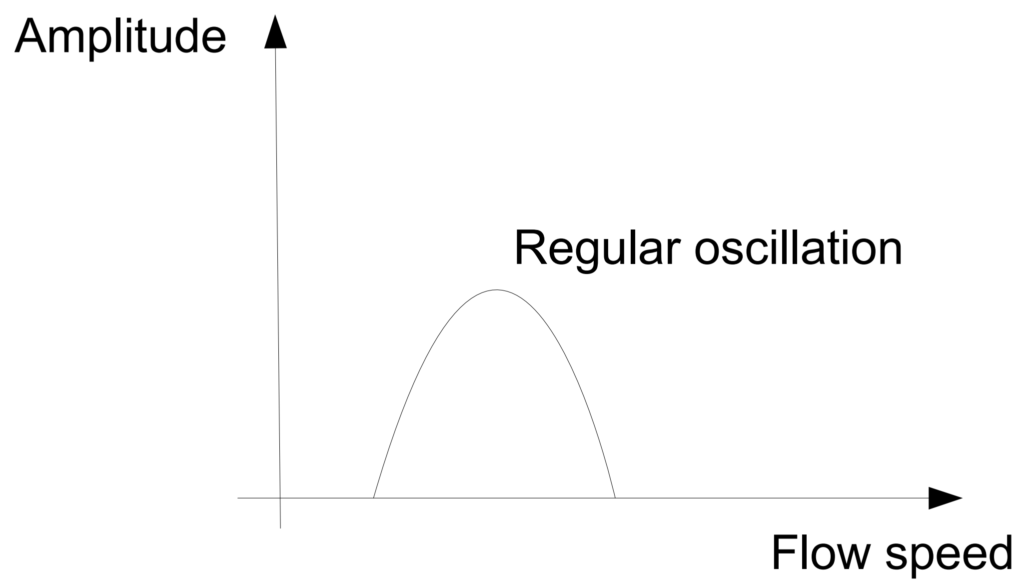
Conclusion on vortex-induced vibration

VIV phomenon predicts vibrations in a frequency range around the fundamental frequency of the oscillator



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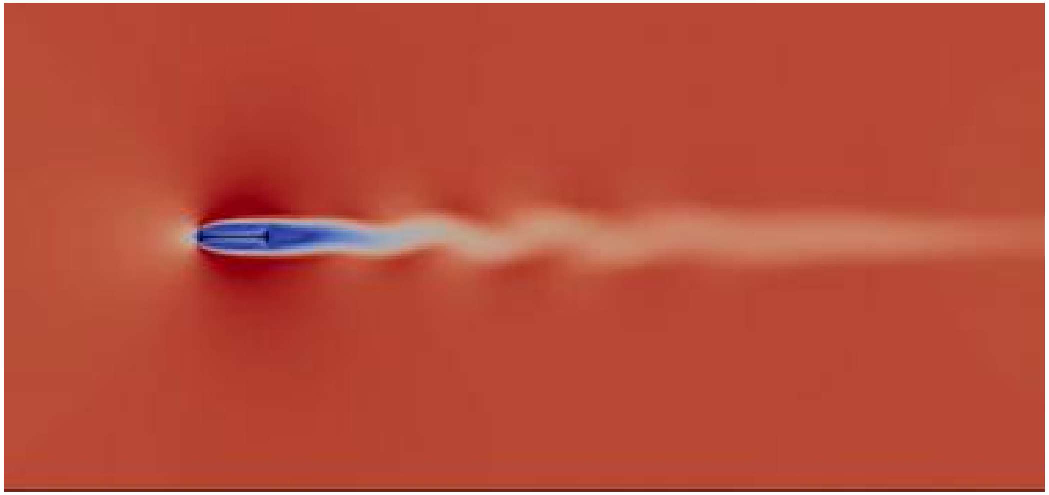
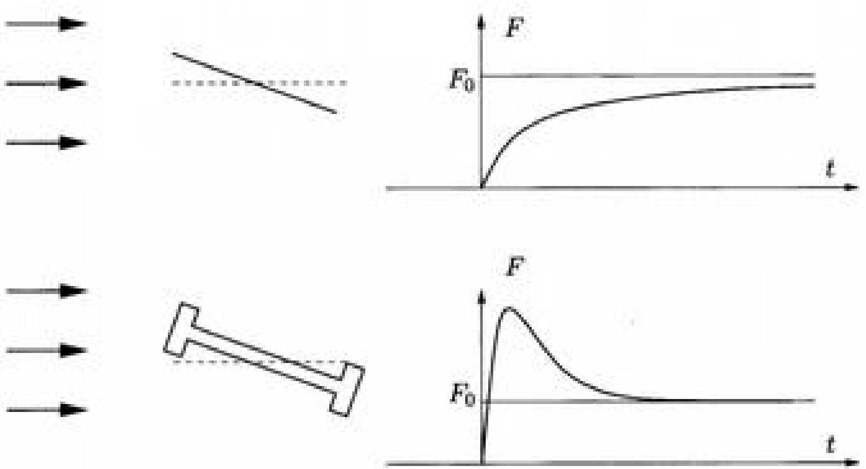
Other instability phenomena



Not a VIV phenomenon !

Flow-structure instationnary dynamics



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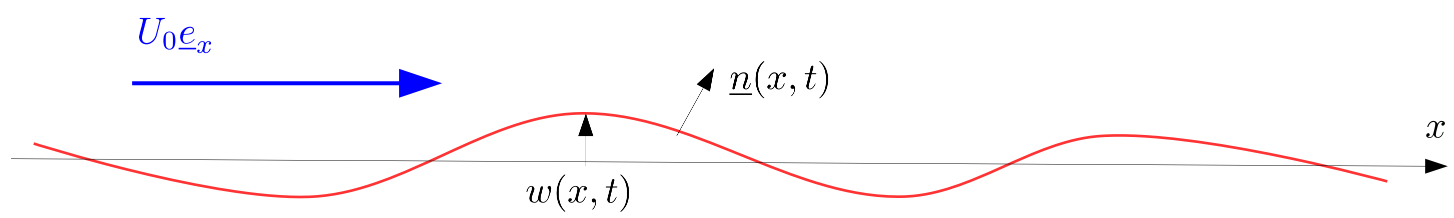
More general continuous problems

→ Axial flow instabilities

Deformation of a boundary in presence of a potential flow



What kind of reactive forces are exerted on the solid ?

- For a displacement of the boundary of the form :

$$w(x,t) = q(t)\phi(x)$$

- Pressure in the fluid :

$$p = -\rho\varphi_2\ddot{q} - \rho U_0\left(\varphi_1 + \frac{\partial\varphi_2}{\partial x}\right)\dot{q} - \rho U_0^2\varphi_1 q$$

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Deformation of a boundary in presence of a potential flow

- Pressure in the fluid :

$$p = -\rho\varphi_2\ddot{q} - \rho U_0\left(\varphi_1 + \frac{\partial\varphi_2}{\partial x}\right)\dot{q} - \rho U_0^2\varphi_1 q$$

- Influence on the mode dynamics → modal force calculation :

General form : $f = \int_S (-p\underline{n}) \,.\, \underline{\phi}\,\mathrm{d}S$

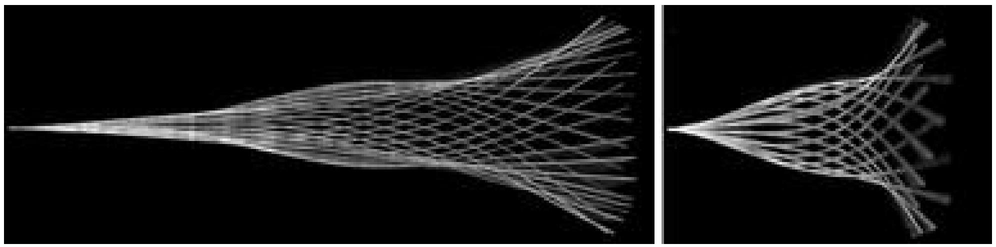
→ Added mass, dissipation, stiffness

- If more than one mode is involved in the dynamics :

Modal force on mode i : $f_i = \sum_j \int_S (-p_j\underline{n}) \,.\, \underline{\phi}_i\,\mathrm{d}S$

→ Coupling through inertia, dissipation and stiffness terms

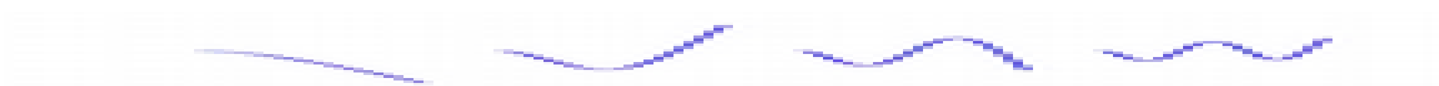
Plates in axial flow



(Eloy et al, 2008)

Fluid-conveying pipe

They can be modeled as beams in axial flow



ϕ_1 ϕ_2 ϕ_3 ϕ_4

The flow couples the modes dynamics through inertia, dissipation and stiffness terms
→ instabilities

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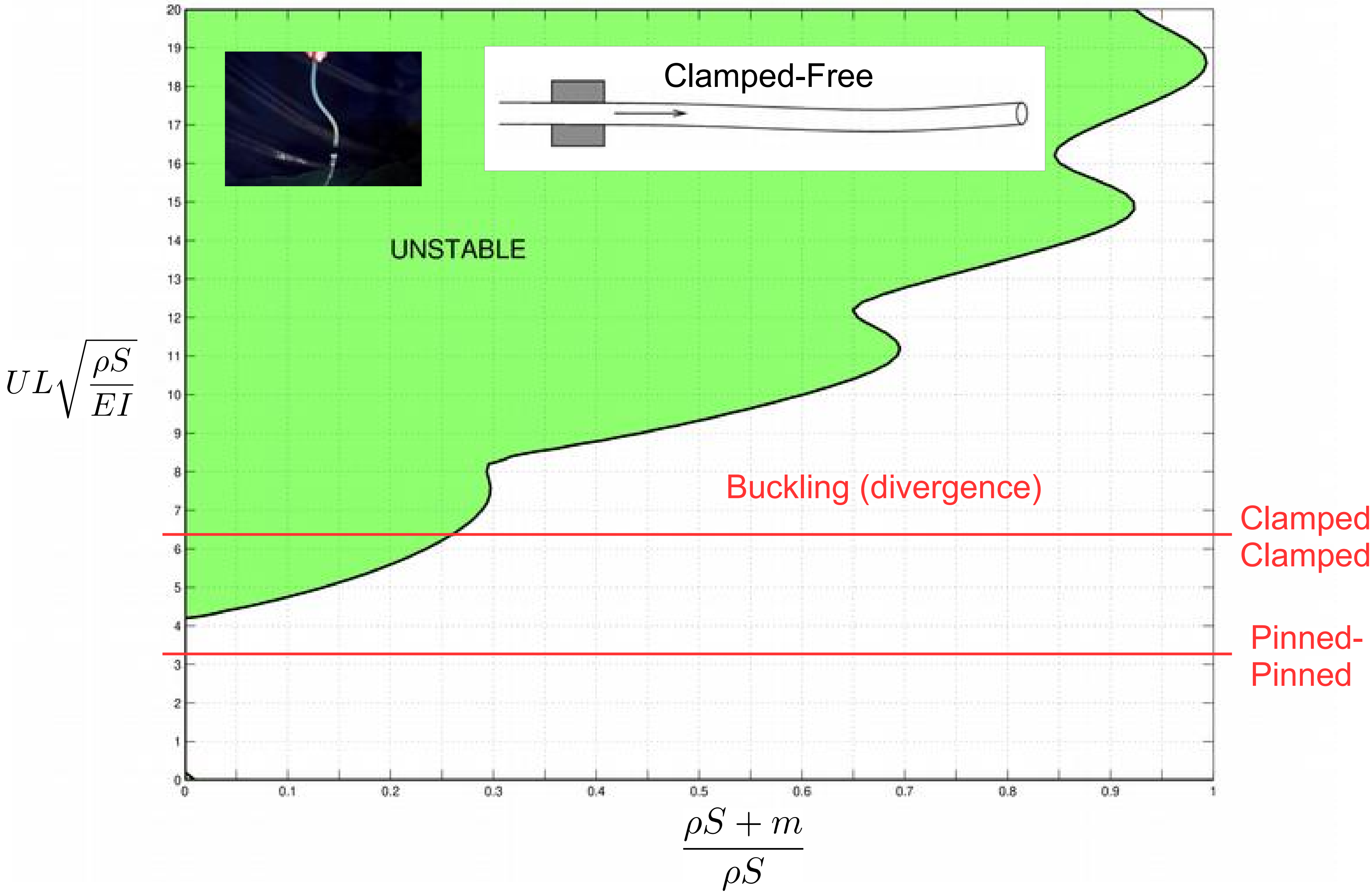
Stability curve



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Conclusion

- **Flow-induced vibrations may have many different origins**

  Negative induced stiffness
  Negative induced damping
  Coupled mode flutter
  Vortex shedding
  Other complex Flow-structure interactions

- **Surrounding flowing fluid may induce**

  Added mass
  Added damping
  Added stiffness

- **Axial flow systems**

  Mode coupling instabilities

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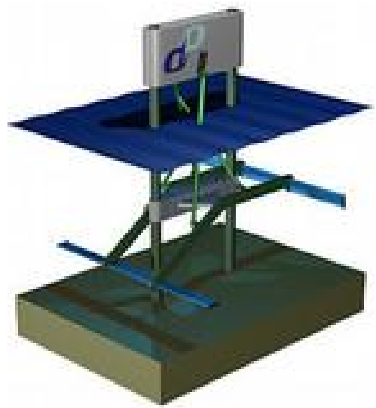
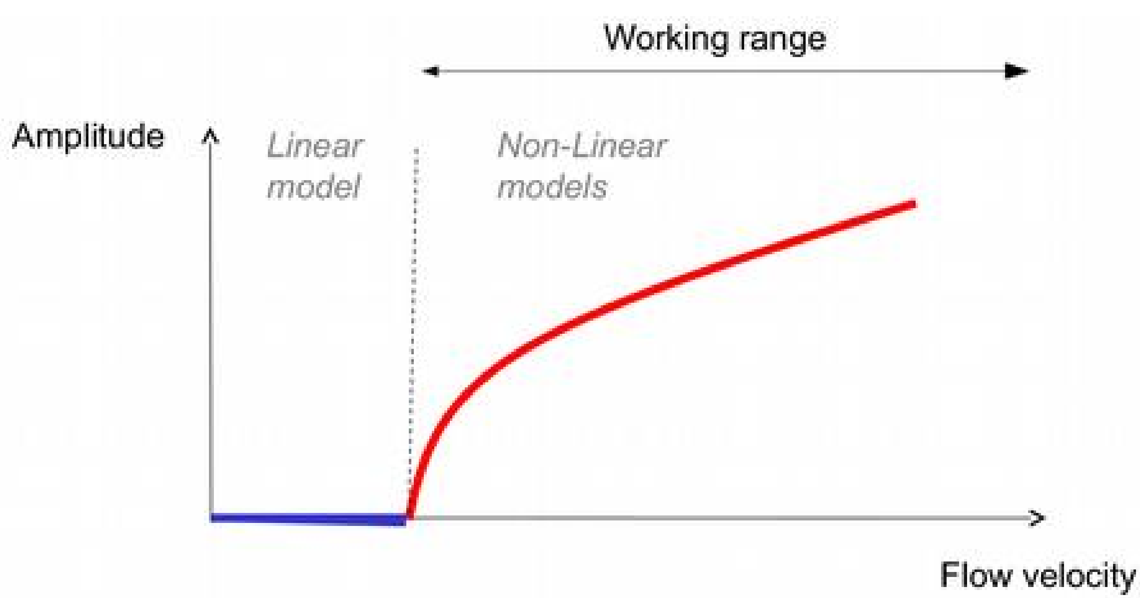
Perspectives



Most of the phenomena are explained by an instability induced by a flow-structure coupling
→ linear phenomena

Energy harvesting → non linear permanent regime



1. The finite amplitude regime depends on the non linear phenomena and the dissipation induced by energy harvesting

2. An optimisation work is necessary to maximise the efficiency of the system

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