Prediction of flutter instability in turbulent flow based on Linear Stability Analysis

J.Moulin, O.Marquet, D.Sipp

Office National d’Etudes et de Recherches Aérospatiales
Département d’Aérodynamique, Aéroélasticité et Aéroacoustique

Funded by *ERC Starting Grant*

BIFD, Houston,12 July 2017

erc
European Research Council
Established by the European Commission

ONERA
THE FRENCH AEROSPACE LAB

Introduction

Fluid-Structure system exhibit various types of **instability** phenomenons

Introduction

Fluid-Structure system exhibit various types of **instability** phenomenons

➢ Accurate fluid-structure modeling is needed

Introduction

Turbulent flows

Streamlined body - **Attached** flow
Heaving and **pitching** involved

Potential flow modelling
Analytical methods [Theodorsen 1935]

Bluff body - **Separated** flow
Only pitching motion involved

No robust modelling
Experiments / Time-marching simulations

As previously mentioned, one of the complications associated with bridge-deck aerodynamics is that the flow will typically separate from the leading edge; hence, analytical methods, such as those presented by Theodorsen (1935) for the flow over airfoils, cannot be employed to determine the aerodynamic derivatives for bridge decks. Although numerical methods (briefly discussed later in this section) are now being proposed, at present, resort must be made to experimental techniques to obtain accurate estimates of the aerodynamic derivatives.

in [Païdoussis 2011]

Introduction

Turbulent flows

Streamlined body - **Attached** flow
Heaving and **pitching** involved

Potential flow modelling
Analytical methods [Theodorsen 1935]

Bluff body - **Separated** flow
Only pitching motion involved

No robust modelling
Experiments / Time-marching simulations

Proposed method

Linear stability analysis of the coupled fluid-structure interaction problem

with a **turbulent flow** modelled with **Reynolds Averaged Navier Stokes** (RANS) equations

Part 1 – Configuration and Modelling

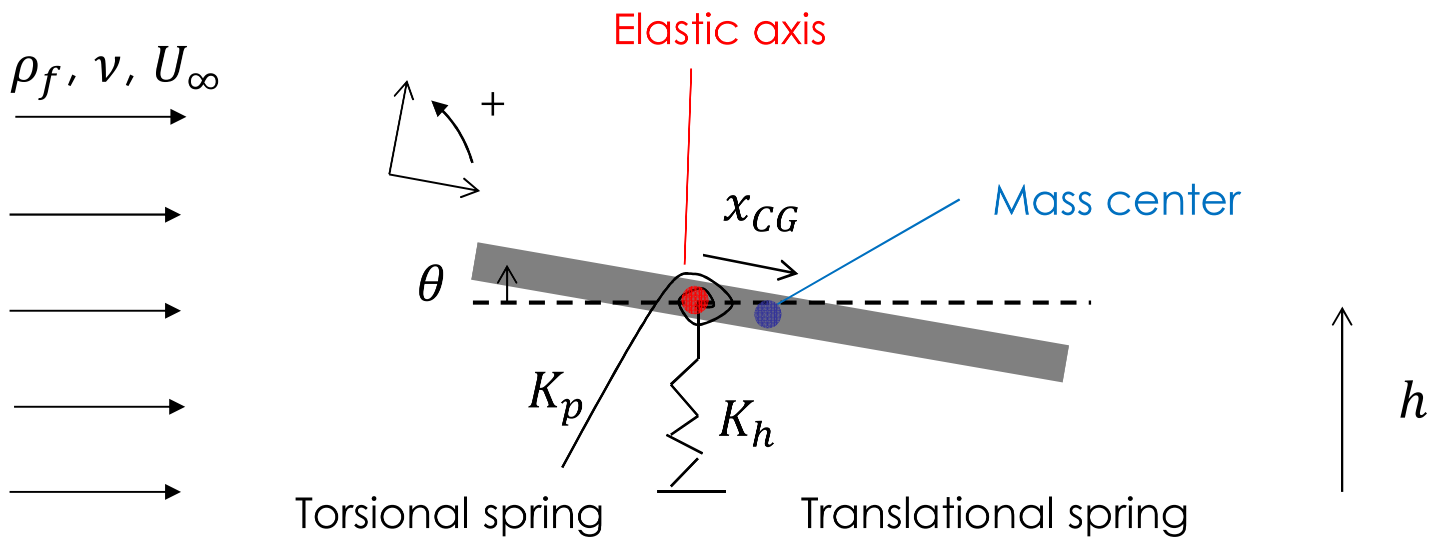
Part 2 –An **elongated plate** mounted on two springs

Part 3 –A **short plate** mounted on two springs

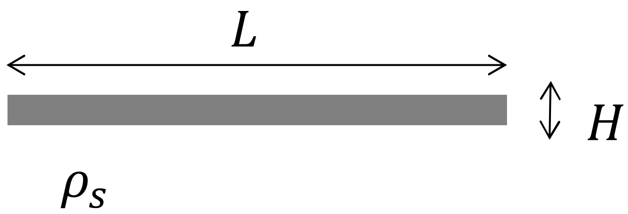
Part 1 : Configuration and Modelling

Aeroelastic configuration

Heaving and **pitching** rigid body in **turbulent incompressible flows**



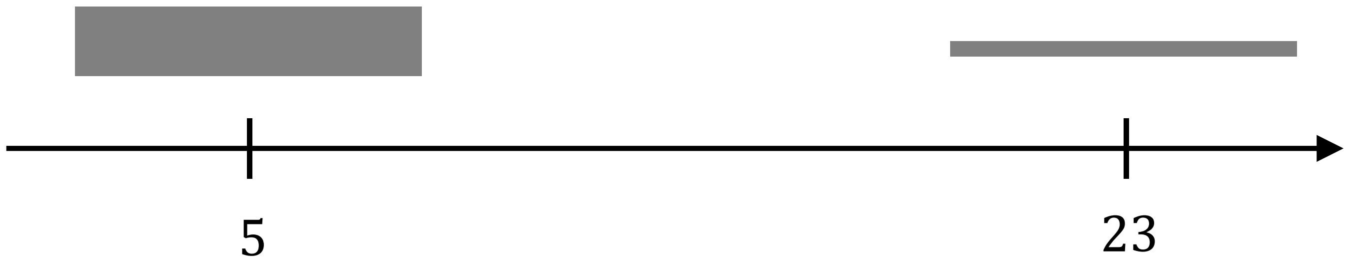
Aeroelastic configuration



$$AR = \frac{L}{H}$$

Two aspect ratios are investigated

Short plate **Elongated plate**



$$AR = \frac{L}{H}$$

« Bridge type » « Airfoil type »

Modelisation

Non-dimensional numbers :

Fluid parameter : $$Re = \frac{LU_\infty}{\nu}$$

Solid parameter :

$$\Omega = \frac{\omega_{0h}}{\omega_{0p}}$$

$\boldsymbol{\omega_{0h}}$: non-dimensional **heaving** natural frequency

$$U^* = \frac{1}{\omega_{0p}}$$

$\boldsymbol{\omega_{0p}}$: non-dimensional **pitching** natural frequency

Coupling parameter : $$\tilde{m} = \frac{\rho_s}{\rho_f}$$

Shape parameters : $$AR = \frac{L}{H} \qquad a = \frac{x_{CG}}{L}$$

Modelisation

Non-dimensional numbers :

Fluid parameter : $Re = 2{,}7 \cdot 10^4$

Solid parameter : $\Omega = 0{,}8$

$$U^* = \frac{1}{\omega_{0p}}$$

Coupling parameter : $\tilde{m} = 10^4$

Shape parameters : $AR = \frac{L}{H}$ $a = 0{,}08$

Fluid-structure modelling

Fluid variables

$$\boldsymbol{q_f}$$

Solid variables

$$\boldsymbol{q_s}$$

Fluid equation

$$\frac{\partial \boldsymbol{q_f}}{\partial t} = \boldsymbol{\mathcal{R}_f}(\boldsymbol{q_f}) + \boldsymbol{C_{fs}}(\boldsymbol{q_f}, \boldsymbol{q_s})$$

Solid equation

$$\frac{d\boldsymbol{q_s}}{dt} = \boldsymbol{C_{sf}}(\boldsymbol{q_f}) + \boldsymbol{\mathcal{R}_s}(\boldsymbol{q_s})$$

Coupled fluid-structure equations

Fluid-structure modelling

Fluid dynamics

- RANS approach
- Spalart-Allmaras turbulent model

$\boldsymbol{q_f} = (u, v, p, \tilde{v})^T$

$$\frac{\partial \boldsymbol{q_f}}{\partial t} = \mathcal{R}_f(\boldsymbol{q_f}) + \boldsymbol{C_{fs}}(\boldsymbol{q_f}, \boldsymbol{q_s})$$

$$\frac{d\boldsymbol{q_s}}{dt} = \boldsymbol{C_{sf}}(\boldsymbol{q_f}) + \mathcal{R}_s(\boldsymbol{q_s})$$

Fluid-structure modelling

Fluid dynamics

- RANS approach
- Spalart-Allmaras turbulent model

$\boldsymbol{q_f} = (u, v, p, \tilde{v})^T$

$$\frac{\partial \boldsymbol{q_f}}{\partial t} = \mathcal{R}_f(\boldsymbol{q_f}) + \boldsymbol{C_{fs}}(\boldsymbol{q_f}, \boldsymbol{q_s})$$

$$\frac{d\boldsymbol{q_s}}{dt} = \boldsymbol{C_{sf}}(\boldsymbol{q_f}) + \mathcal{R}_s(\boldsymbol{q_s})$$

$\boldsymbol{q_s} = (h, \theta, \dot{h}, \dot{\theta})^T$

Solid dynamics

- 2-DOF rigid body

$$\ddot{h} + \omega_{0h}^2\, h + a\, \ddot{\theta} = 0$$

$$\ddot{\theta} + \omega_{0p}^2\, \theta + f(a)\, \ddot{h} = 0$$

Fluid-structure modelling

Fluid dynamics

- RANS approach
- Spalart-Allmaras turbulent model

Solid-to-fluid coupling

- Interface conditions
- Non-inertial volumic terms [Mougin et al. 2002]

$\boldsymbol{q_f} = (u, v, p, \tilde{\nu})^T$

$$\frac{\partial \boldsymbol{q_f}}{\partial t} = \mathcal{R}_f(\boldsymbol{q_f}) + \boldsymbol{C}_{fs}(\boldsymbol{q_f}, \boldsymbol{q_s})$$

$$\frac{d\boldsymbol{q_s}}{dt} = \boldsymbol{C}_{sf}(\boldsymbol{q_f}) + \mathcal{R}_s(\boldsymbol{q_s})$$

$\boldsymbol{q_s} = (h, \theta, \dot{h}, \dot{\theta})^T$

Fluid-to-solid coupling

- Fluid force - Lift
- Fluid moment

Solid dynamics

- 2-DOF rigid body

$$\ddot{h} + \omega_{0h}^2\, h + a\, \ddot{\theta} = 0$$

$$\ddot{\theta} + \omega_{0p}^2\, \theta + f(a)\, \ddot{h} = 0$$

Linear stability analysis

Two classical ingredients :

Perturbation decomposition

Fluid $\boldsymbol{q_f}(\boldsymbol{x}, t) = \boldsymbol{Q_f}(\boldsymbol{x}) + \epsilon\, \boldsymbol{q'_f}(\boldsymbol{x}, t)$

Solid $\boldsymbol{q_s}(t) = \boldsymbol{0} + \epsilon\, \boldsymbol{q'_s}(t)$

base state perturbation

Modal decomposition

Fluid $\boldsymbol{q'_f}(\boldsymbol{x}, \boldsymbol{t}) = \boldsymbol{\hat{q}_f}(\boldsymbol{x})\ \boldsymbol{e}^{\sigma t} + c.c$

Solid $\boldsymbol{q'_s}(\boldsymbol{t}) = \boldsymbol{\hat{q}_s}\ \boldsymbol{e}^{\sigma t} + c.c$

Linear stability analysis

Growth rate

$\lambda = \Re[\sigma]$

Frequency

$\omega = \Im[\sigma]$

Fluid-solid mode

$(\hat{\boldsymbol{q}}_f, \hat{\boldsymbol{q}}_s)$

Coupled eigenvalue problem

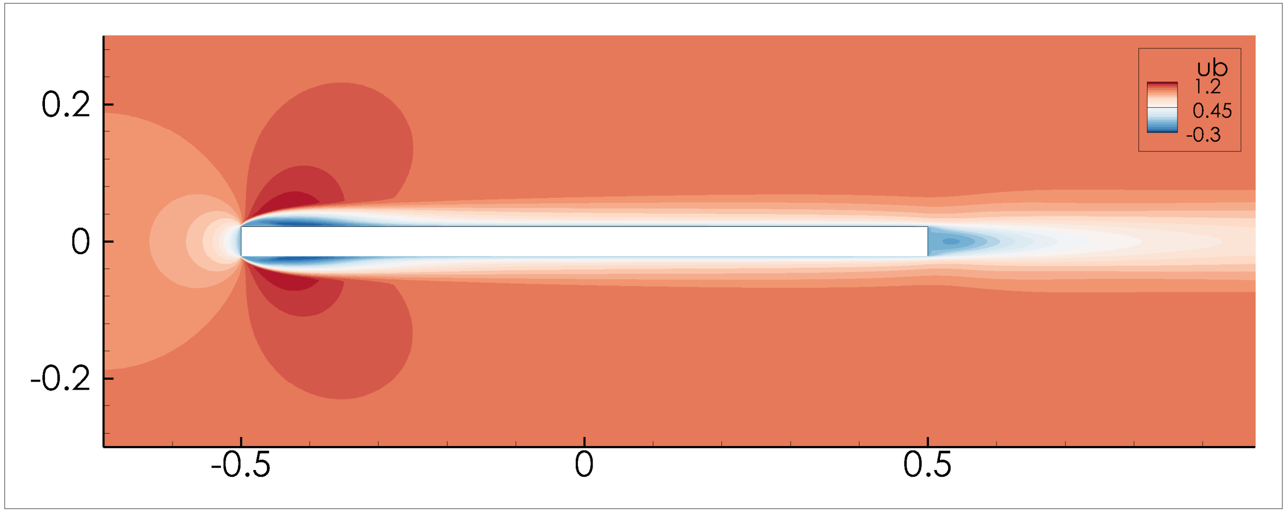
$$\sigma\, B \begin{pmatrix} \hat{\boldsymbol{q}}_f \\ \hat{\boldsymbol{q}}_s \end{pmatrix} = \underbrace{\begin{pmatrix} A_{ff} & A_{fs} \\ A_{sf} & A_{ss} \end{pmatrix}}_{} \begin{pmatrix} \hat{\boldsymbol{q}}_f \\ \hat{\boldsymbol{q}}_s \end{pmatrix}$$

Mass matrix (spatial discretizarion)

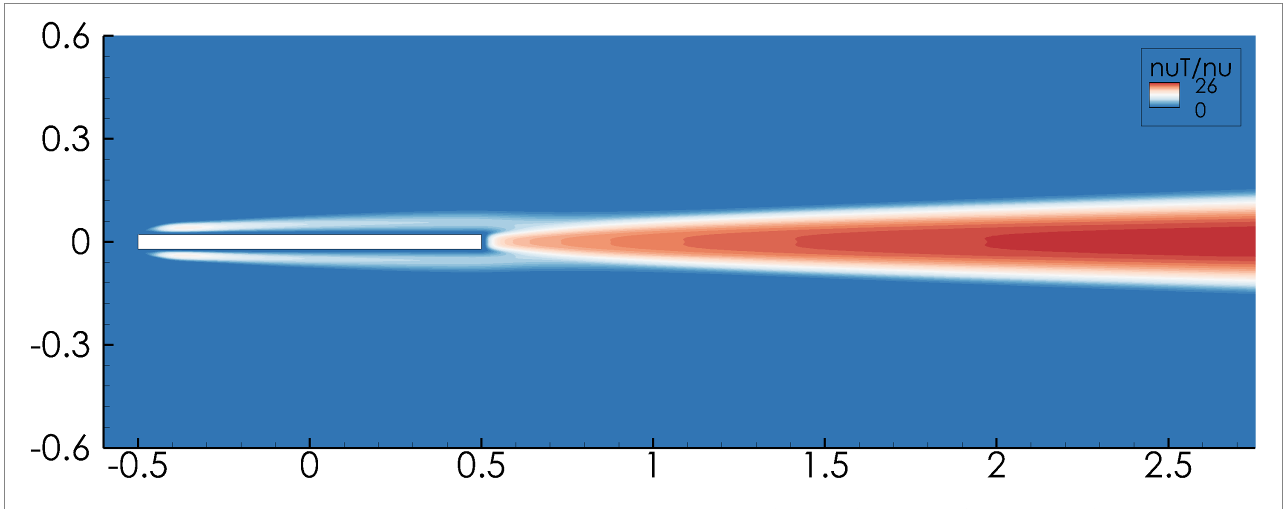
Fluid-structure Jacobian matrix

Part 2 : An **elongated plate** mounted on two springs (AR=23)

Steady base flow

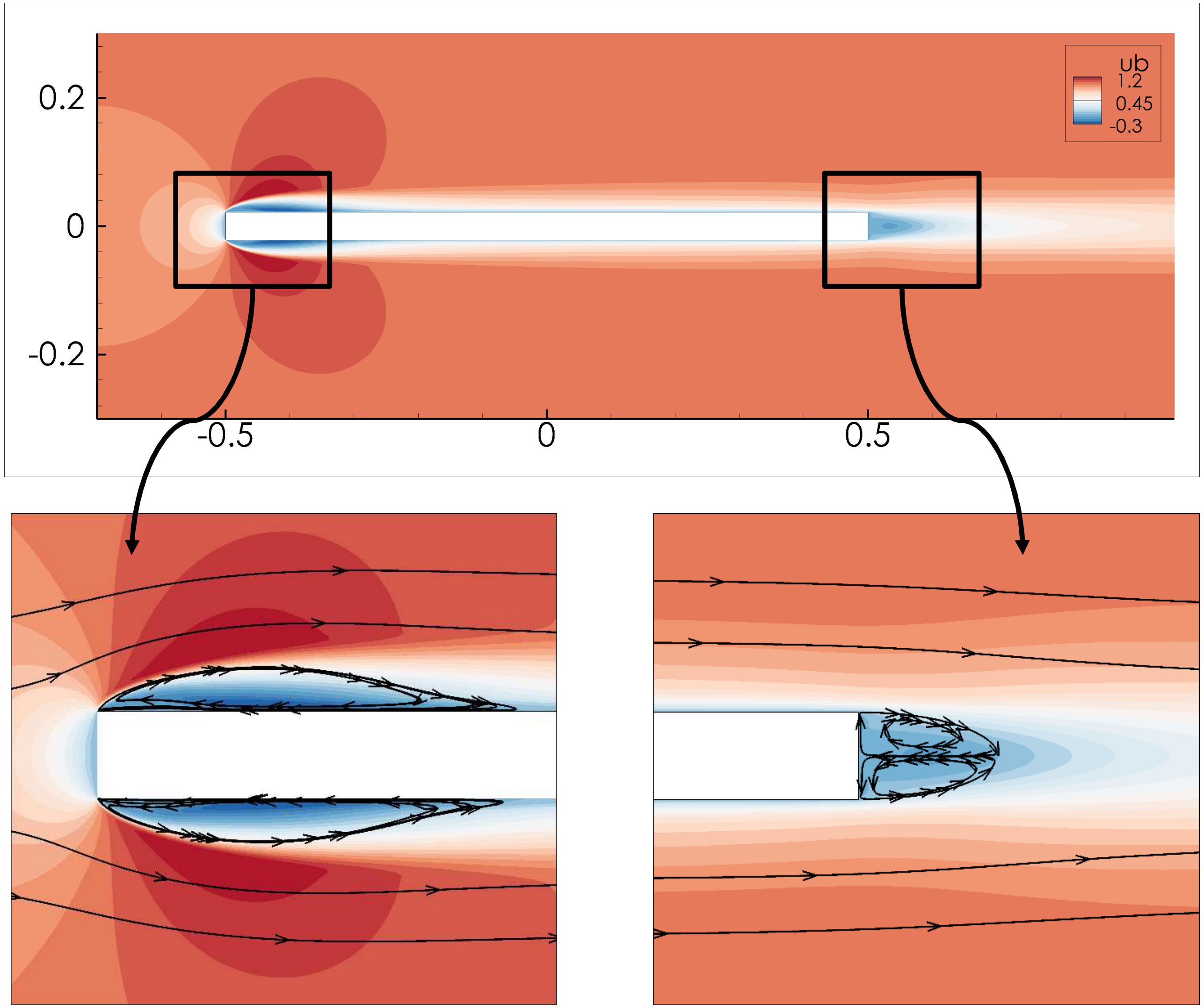


Axial velocity ($Re = 27500$)



Turbulent to kinematic viscosity ratio

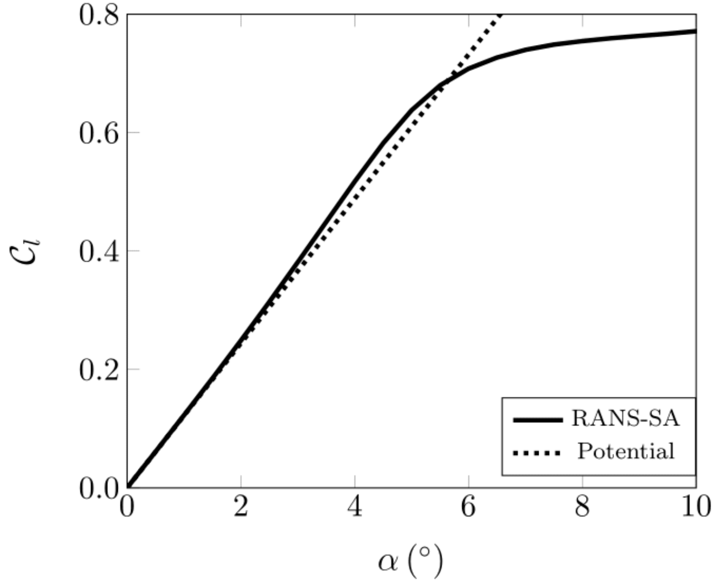
Steady base flow



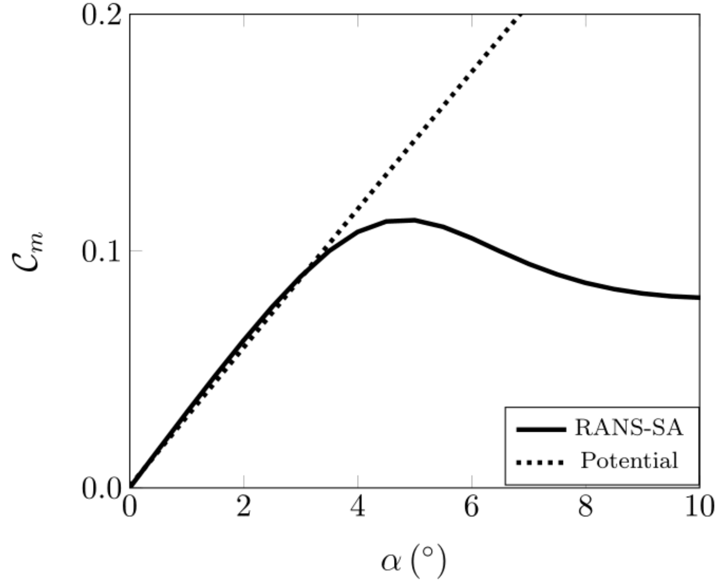
ONERA
THE FRENCH AEROSPACE LAB

Steady base flow

Lift coefficient



Moment coefficient

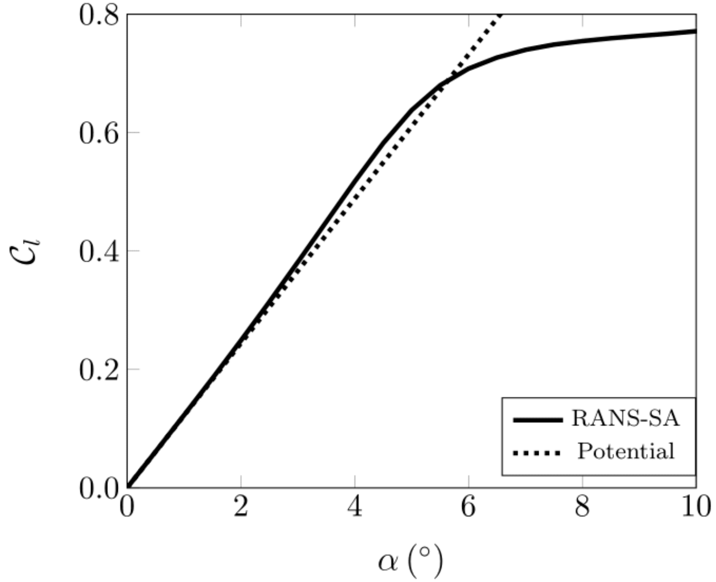


	$\left.\frac{\partial C_l}{\partial \alpha}\right\|_{\alpha=0}$	$\left.\frac{\partial C_m}{\partial \alpha}\right\|_{\alpha=0}$
Present study	**7,0**	**1,8**
Potential flows	7,0	1,7

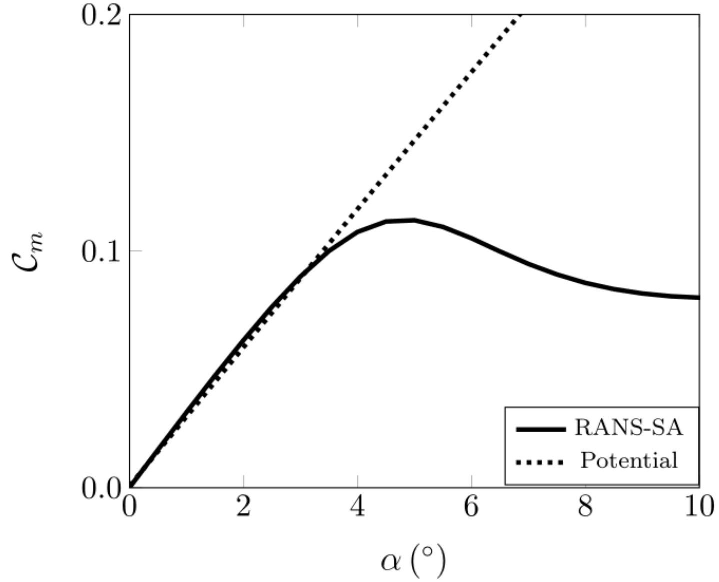
ONERA THE FRENCH AEROSPACE LAB

Steady base flow

Lift coefficient



Moment coefficient



	$\left.\frac{\partial C_l}{\partial \alpha}\right\|_{\alpha=0}$	$\left.\frac{\partial C_m}{\partial \alpha}\right\|_{\alpha=0}$
Present study	**7,0**	**1,8**
Potential flows	7,0	1,7

→ **Small influence of detached areas** on slopes at $\alpha = 0°$

Linear Stability Analysis

Coupled fluid-structure system

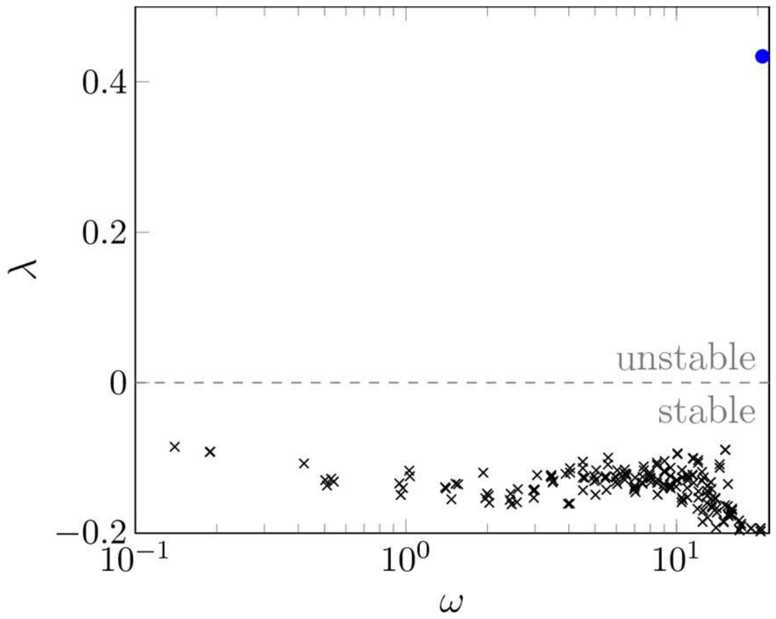
$$\sigma \boldsymbol{B}\hat{\boldsymbol{q}} = \boldsymbol{A}\hat{\boldsymbol{q}}$$

$$\boldsymbol{A} = \begin{pmatrix} \boldsymbol{A}_{ff} & \boldsymbol{A}_{fs} \\ \boldsymbol{A}_{sf} & \boldsymbol{A}_{ss} \end{pmatrix}$$

Linear Stability Analysis

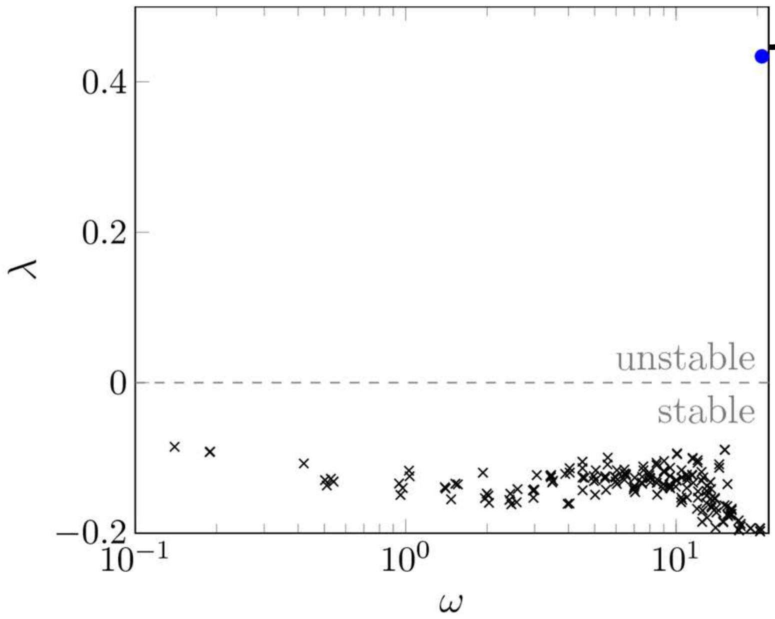
Uncoupled fluid system

$$\sigma_f \boldsymbol{B}_{ff} \widehat{\boldsymbol{q}}_{\boldsymbol{f}} = \boldsymbol{A}_{ff} \widehat{\boldsymbol{q}}_{\boldsymbol{f}}$$

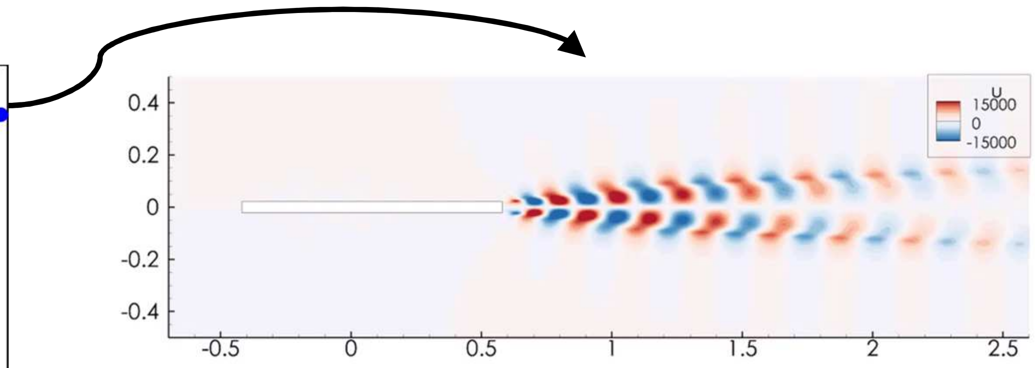


Fluid system spectrum

Uncoupled fluid system $\sigma_f \boldsymbol{B}_{ff}\hat{\boldsymbol{q}}_f = \boldsymbol{A}_{ff}\hat{\boldsymbol{q}}_f$

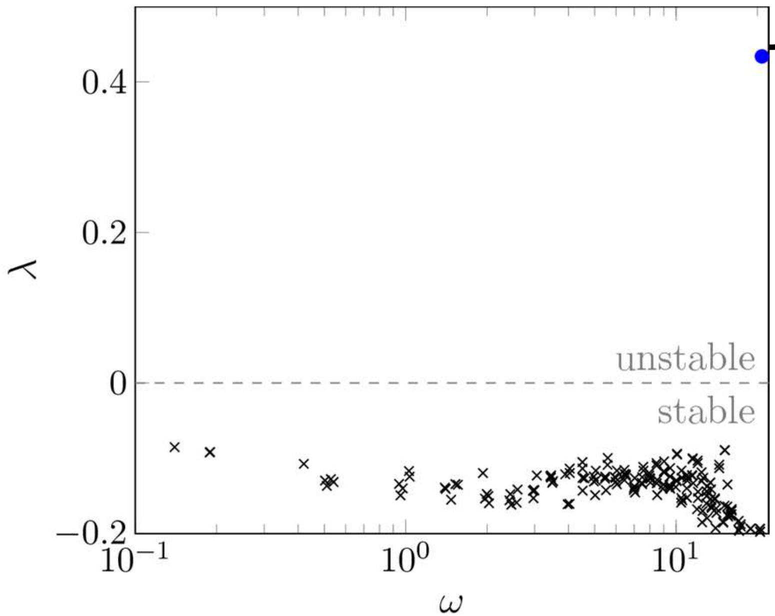


Fluid system spectrum

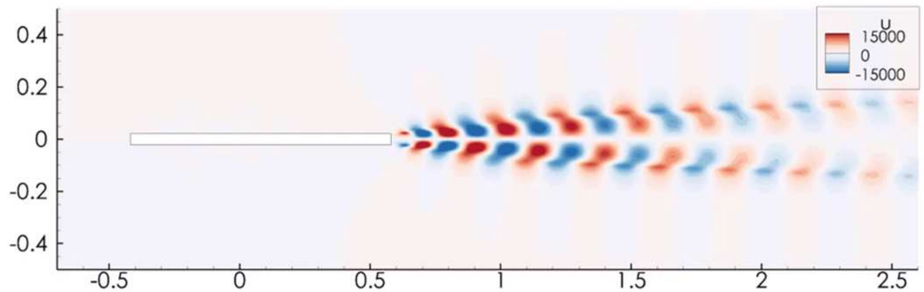


Linear Stability Analysis

Uncoupled fluid system $\quad \sigma_f \boldsymbol{B}_{ff} \widehat{\boldsymbol{q}}_f = \boldsymbol{A}_{ff} \widehat{\boldsymbol{q}}_f$



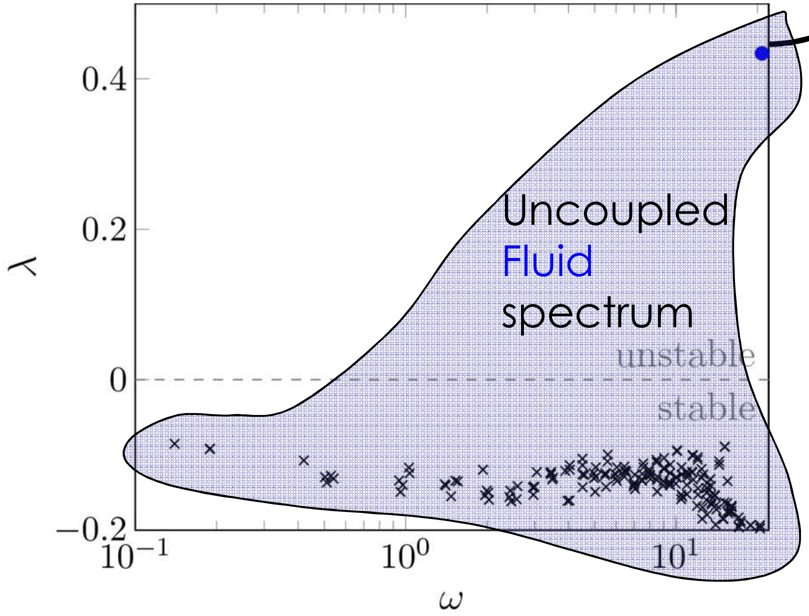
Fluid system spectrum



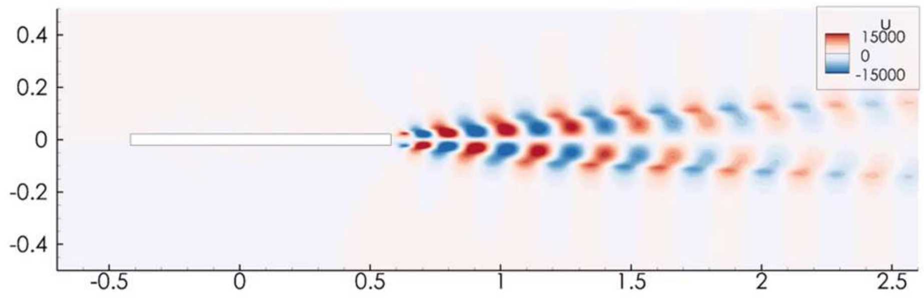
$\omega = 20{,}7 \quad (St_H \simeq 0{,}14)$

Linear Stability Analysis

Uncoupled fluid system $\sigma_f \boldsymbol{B}_{ff}\hat{\boldsymbol{q}}_f = \boldsymbol{A}_{ff}\hat{\boldsymbol{q}}_f$



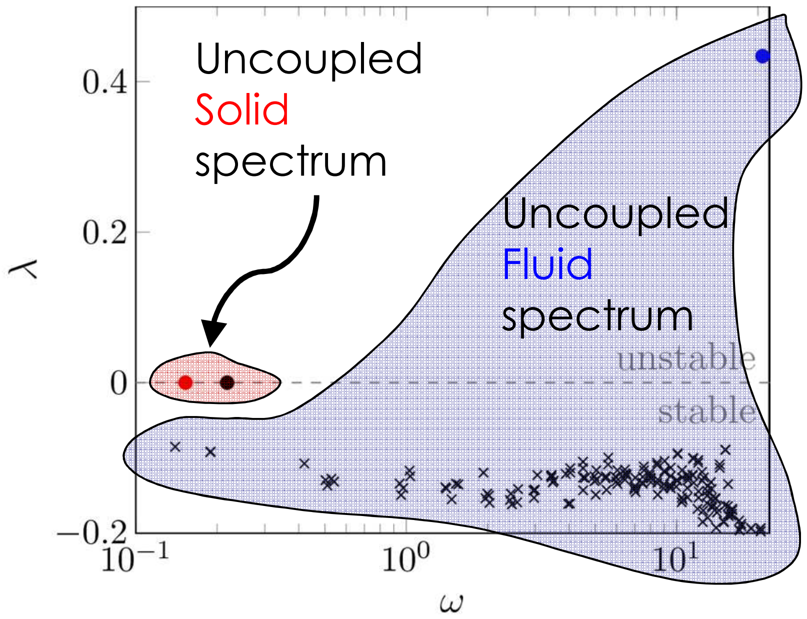
Fluid system spectrum



$\omega = 20{,}7 \quad (St_H \simeq 0{,}14)$

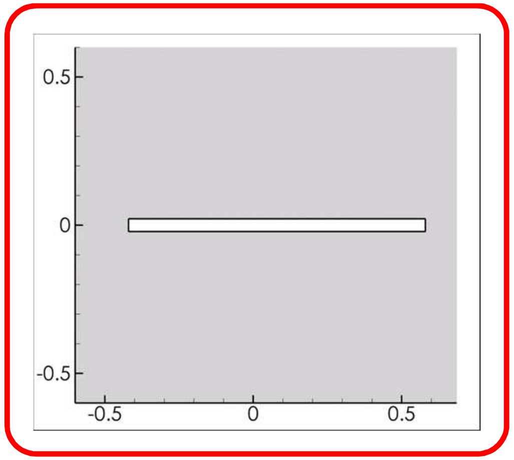
Linear Stability Analysis

Uncoupled solid system $\sigma_s \boldsymbol{B}_{ss} \widehat{\boldsymbol{q}}_s = \boldsymbol{A}_{ss} \widehat{\boldsymbol{q}}_s$



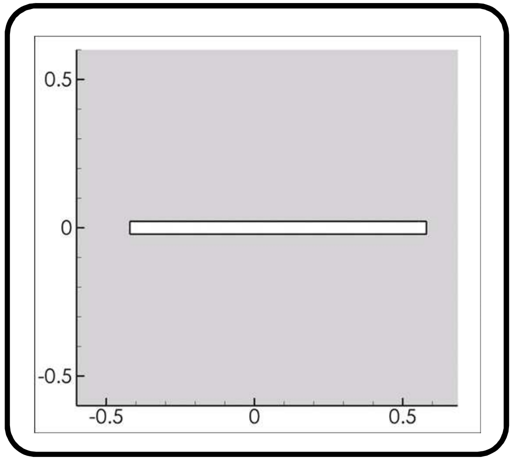
$U^* = 5$

Low-frequency mode



$\frac{\omega}{\omega_{0p}} = 0{,}76$

High-frequency mode

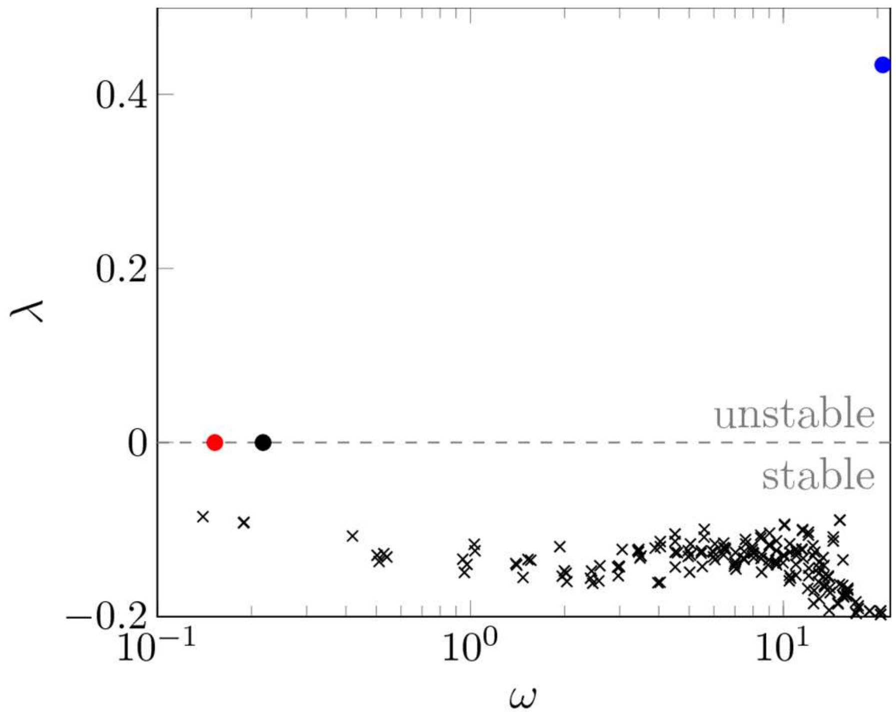


$\frac{\omega}{\omega_{0p}} = 1{,}08$

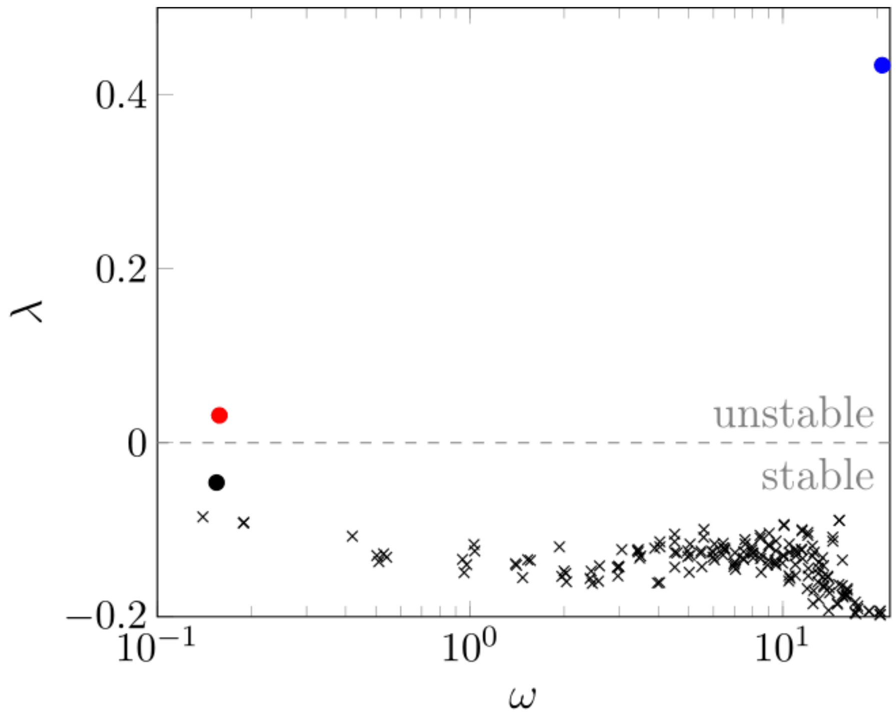
- **Inertial coupling** bewteen heaving and pitching

Linear Stability Analysis

Uncoupled fluid and solid systems



Coupled fluid-structure system

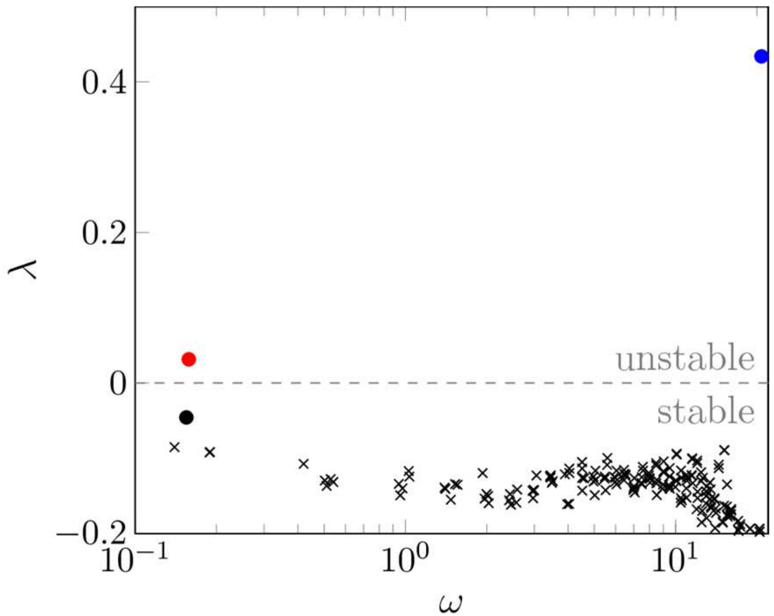


Linear Stability Analysis

Coupled fluid-structure system

$$\sigma \boldsymbol{B}\hat{\boldsymbol{q}} = \boldsymbol{A}\hat{\boldsymbol{q}}$$

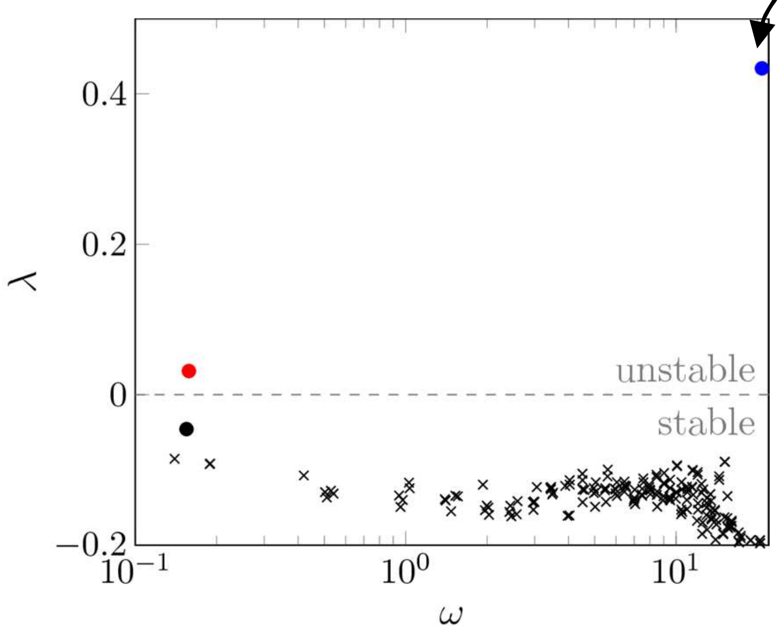
$$\boldsymbol{A} = \begin{pmatrix} \boldsymbol{A}_{ff} & \boldsymbol{A}_{fs} \\ \boldsymbol{A}_{sf} & \boldsymbol{A}_{ss} \end{pmatrix}$$

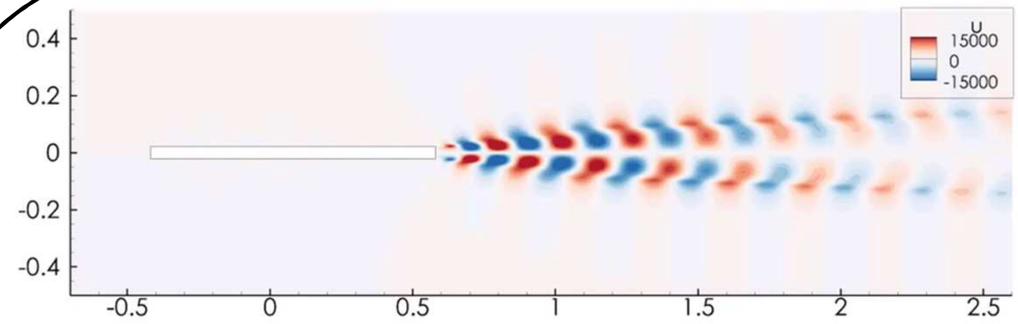


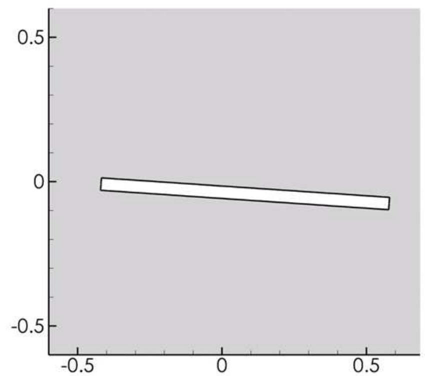
$U^* = 5 \qquad \tilde{m} = 10^4$

Linear Stability Analysis

Coupled fluid-structure system $\quad \sigma\hat{\boldsymbol{q}} = \boldsymbol{A}\hat{\boldsymbol{q}} \quad \boldsymbol{A} = \begin{pmatrix} \boldsymbol{A}_{ff} & \boldsymbol{A}_{fs} \\ \boldsymbol{A}_{sf} & \boldsymbol{A}_{ss} \end{pmatrix}$







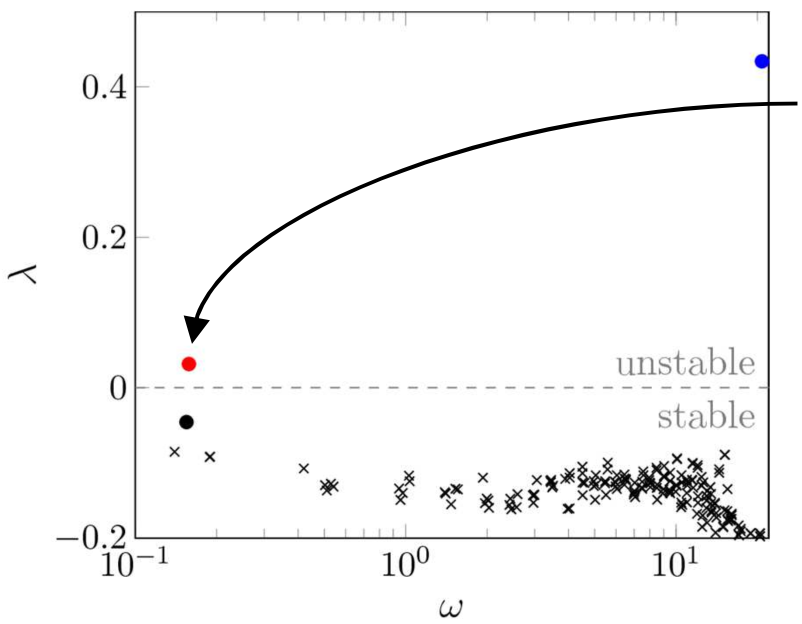
Mode kinetic energy : $E_s = 1 \quad E_f = 10^8$

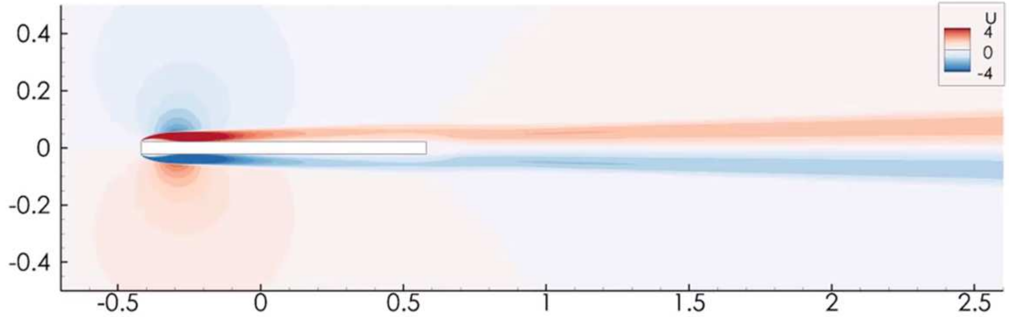
Linear Stability Analysis

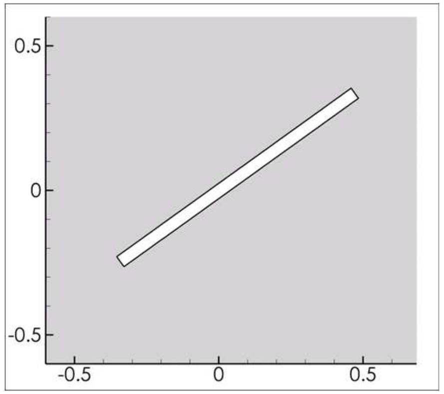
Coupled fluid-structure system

$$\sigma \hat{\boldsymbol{q}} = \boldsymbol{A}\hat{\boldsymbol{q}}$$

$$\boldsymbol{A} = \begin{pmatrix} \boldsymbol{A}_{ff} & \boldsymbol{A}_{fs} \\ \boldsymbol{A}_{sf} & \boldsymbol{A}_{ss} \end{pmatrix}$$



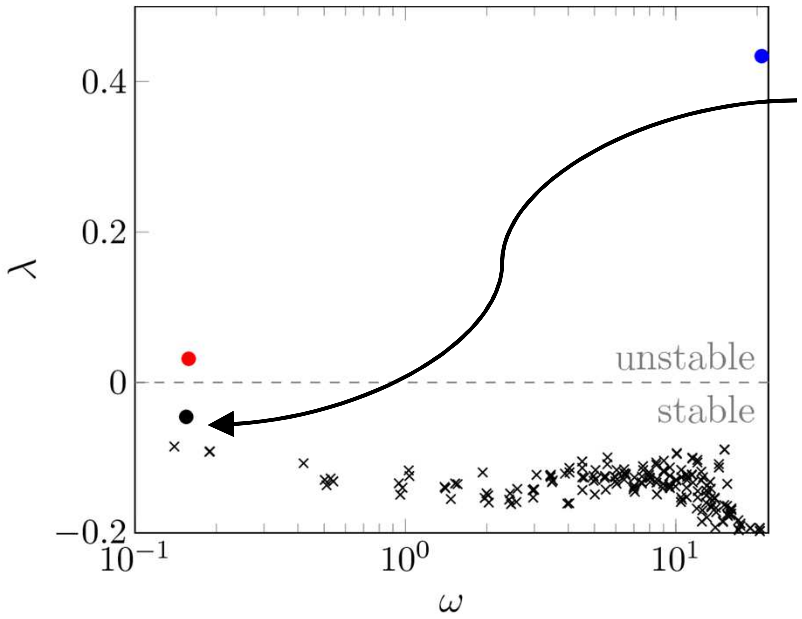


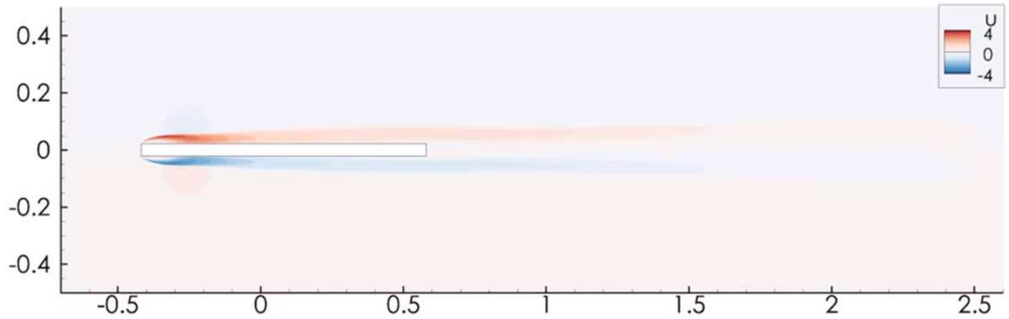


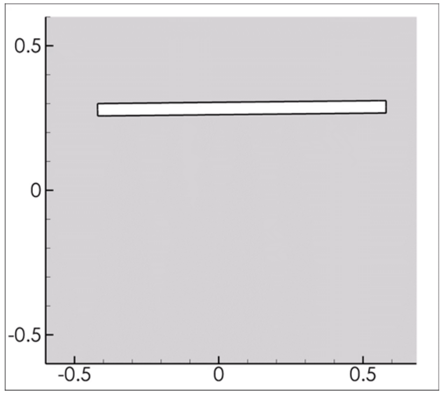
Mode kinetic energy : $E_s = 1$ $E_f = 4{,}1$

Linear Stability Analysis

Coupled fluid-structure system $\quad \sigma\hat{\boldsymbol{q}} = \boldsymbol{A}\hat{\boldsymbol{q}} \quad \boldsymbol{A} = \begin{pmatrix} \boldsymbol{A}_{ff} & \boldsymbol{A}_{fs} \\ \boldsymbol{A}_{sf} & \boldsymbol{A}_{ss} \end{pmatrix}$

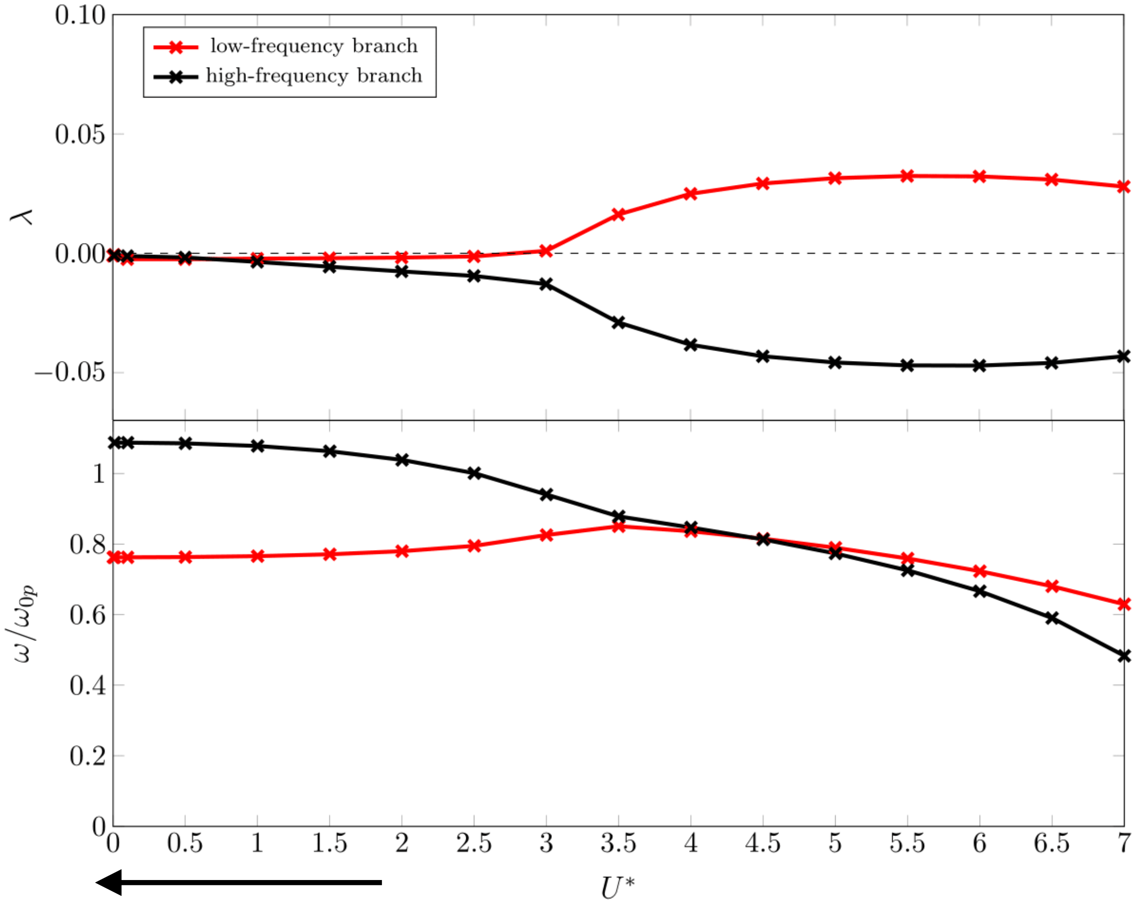






Mode kinetic energy : $E_s = 1 \qquad E_f = 1{,}1$

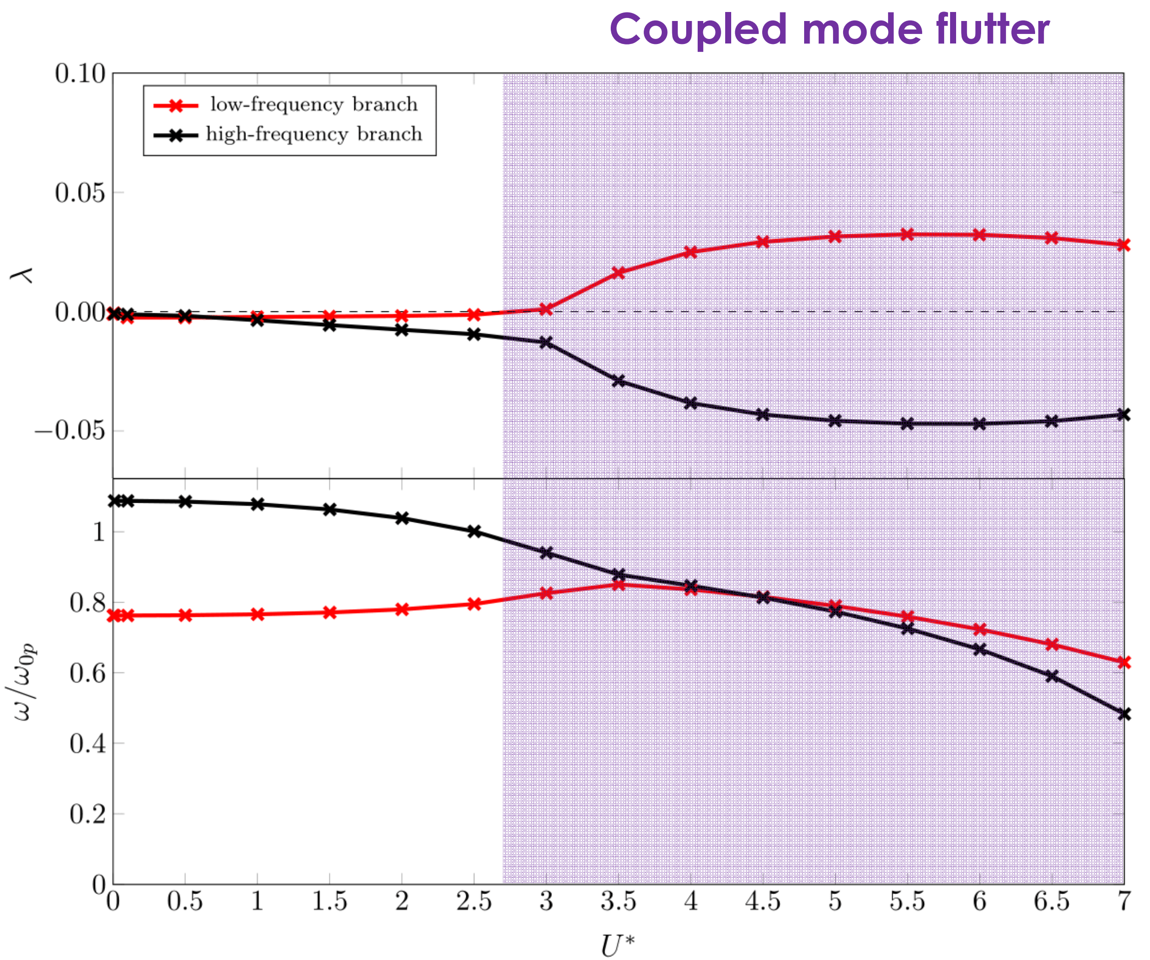
Aeroelastic instabilities of a 2-DOF elongated plate



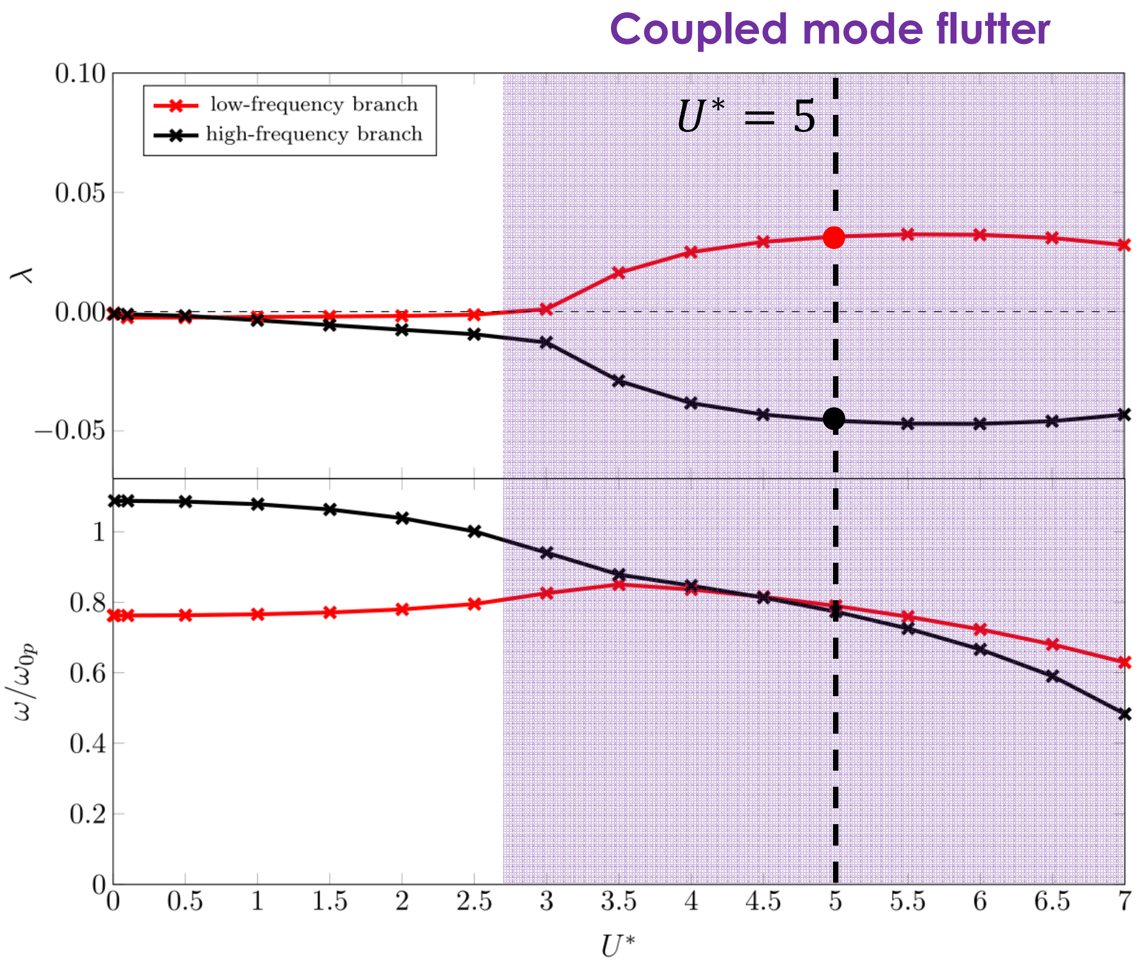
$U^* \rightarrow 0$:

uncoupled case

Aeroelastic instabilities of a 2-DOF elongated plate



Aeroelastic instabilities of a 2-DOF elongated plate

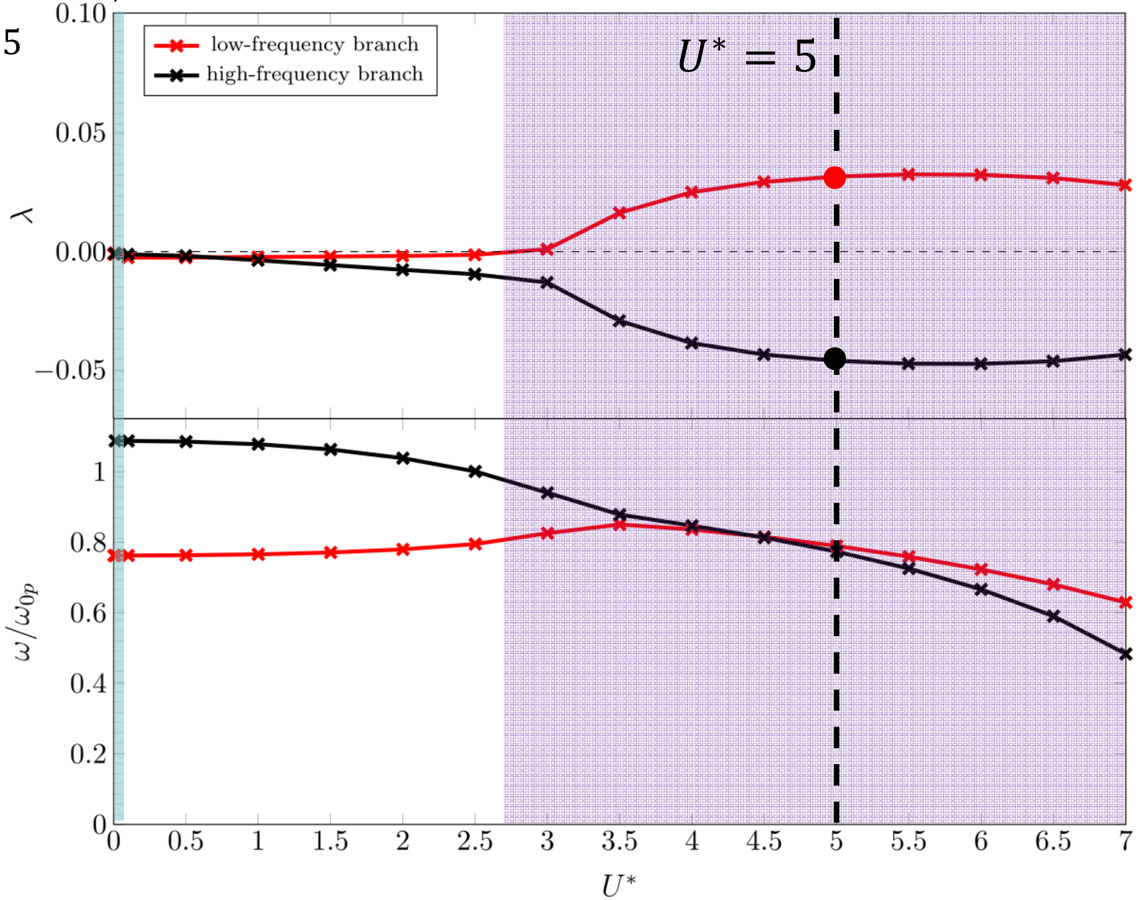


Aeroelastic instabilities of a 2-DOF elongated plate

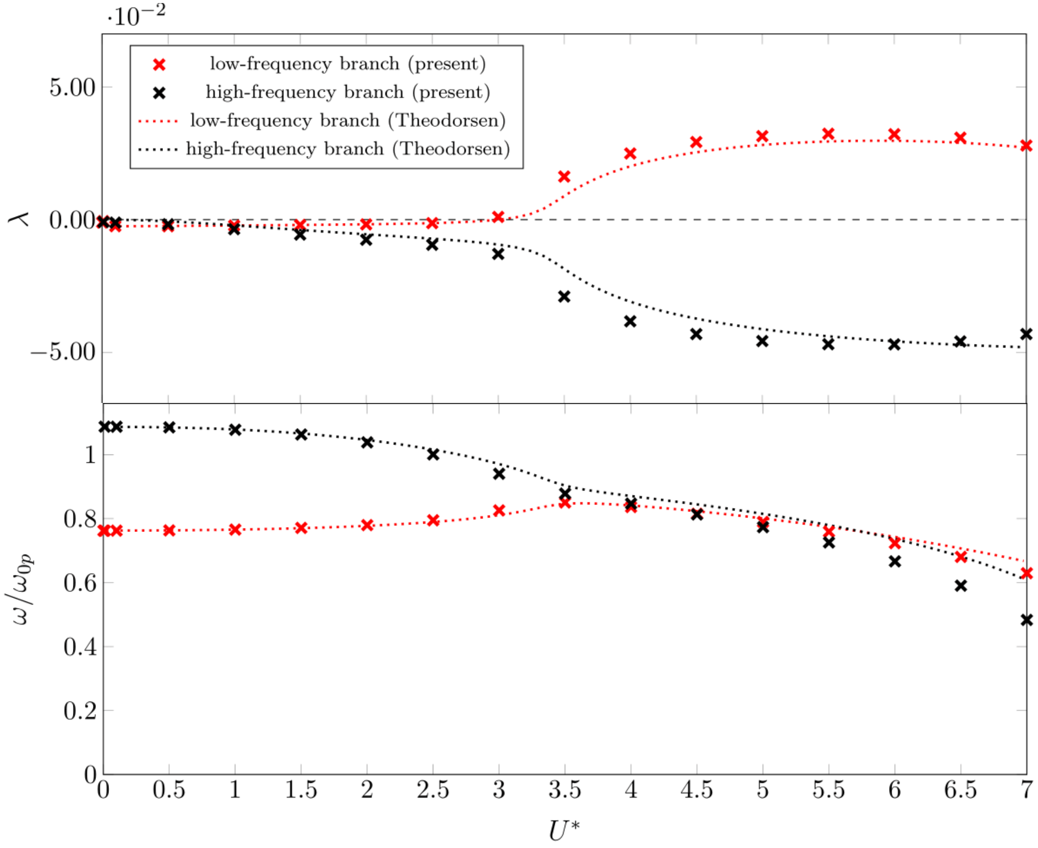
VIV
(not investigated here)

$$U^*_{VIV} \simeq \frac{1}{2\pi \, St_H \, AR} \simeq 0{,}05$$

Coupled mode flutter



Validation



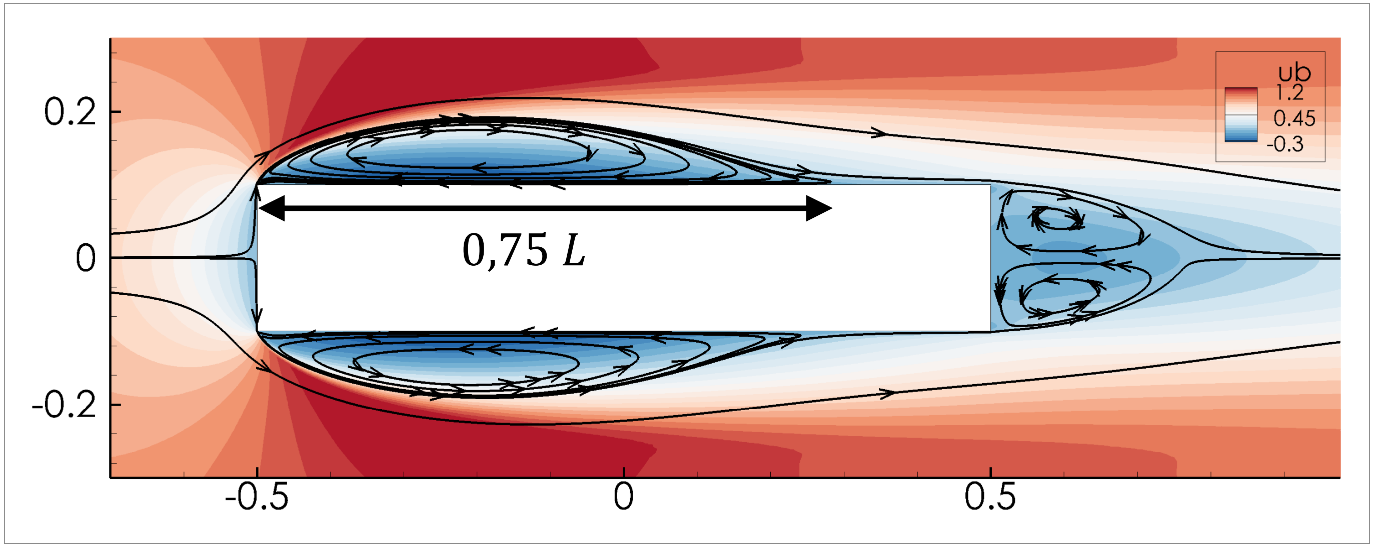
	U^*_{crit}	$\frac{\omega}{\omega_{0p}}$
Present study	**2,9**	**0,81**
Theodorsen	3,0	0,81

Comparison to Theodorsen model

- Modelisation **validated against** classical **Theodorsen** flutter theory
- **Maginal role of detached areas** on instability thresholds

Part 3 : An **short plate** mounted on two springs (AR=5)

Steady Base Flow

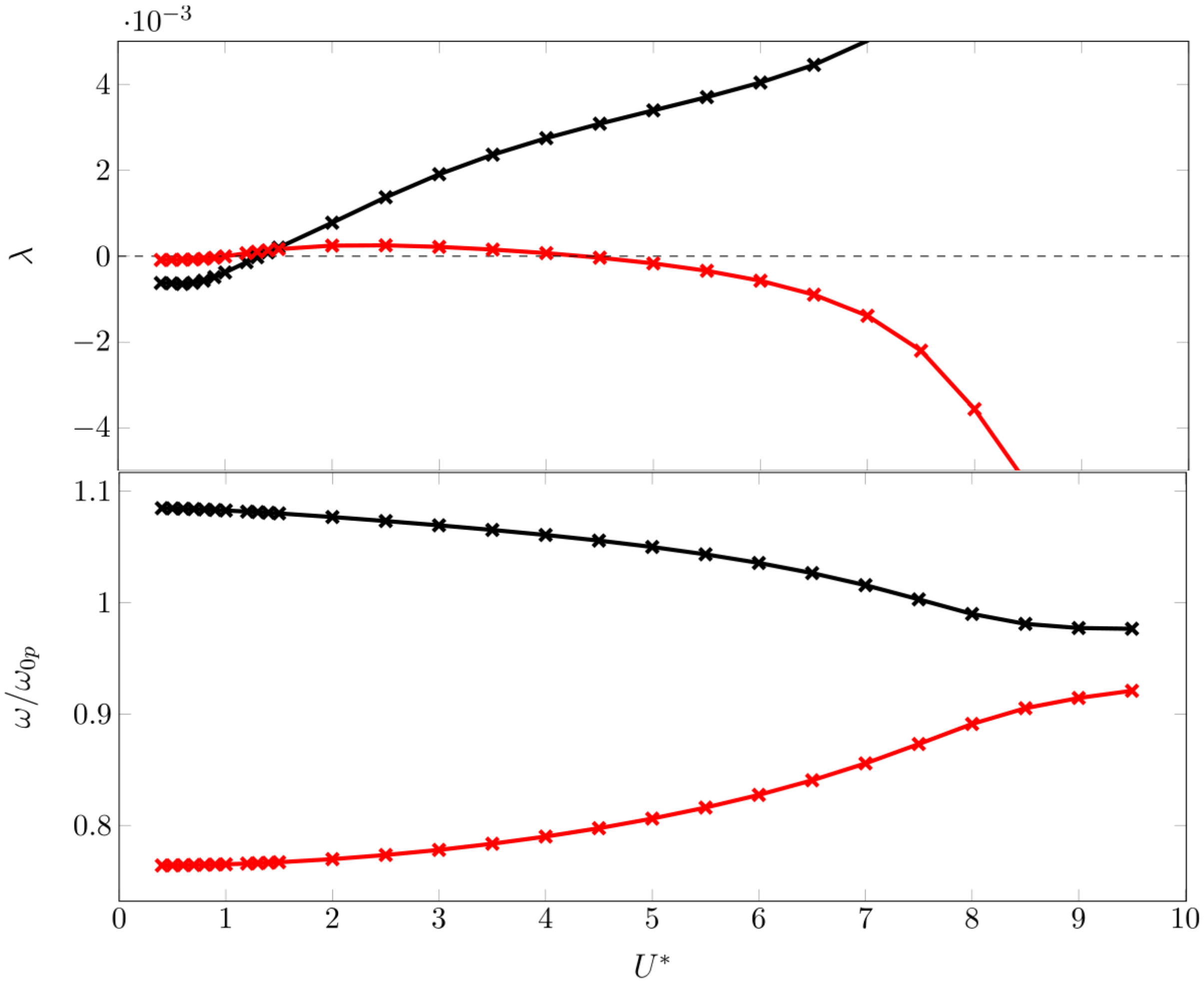


	$\left.\frac{\partial C_l}{\partial \alpha}\right\|_{\alpha=0}$	$\left.\frac{\partial C_m}{\partial \alpha}\right\|_{\alpha=0}$
Present study	**9,15**	**0,95**
Potential flows	8,4	1,7

Large leading-edge **detached areas**

- Non-negligible effect on steady aerodynamic coefficient

Aeroelastic instabilities of a 2-DOF short plate



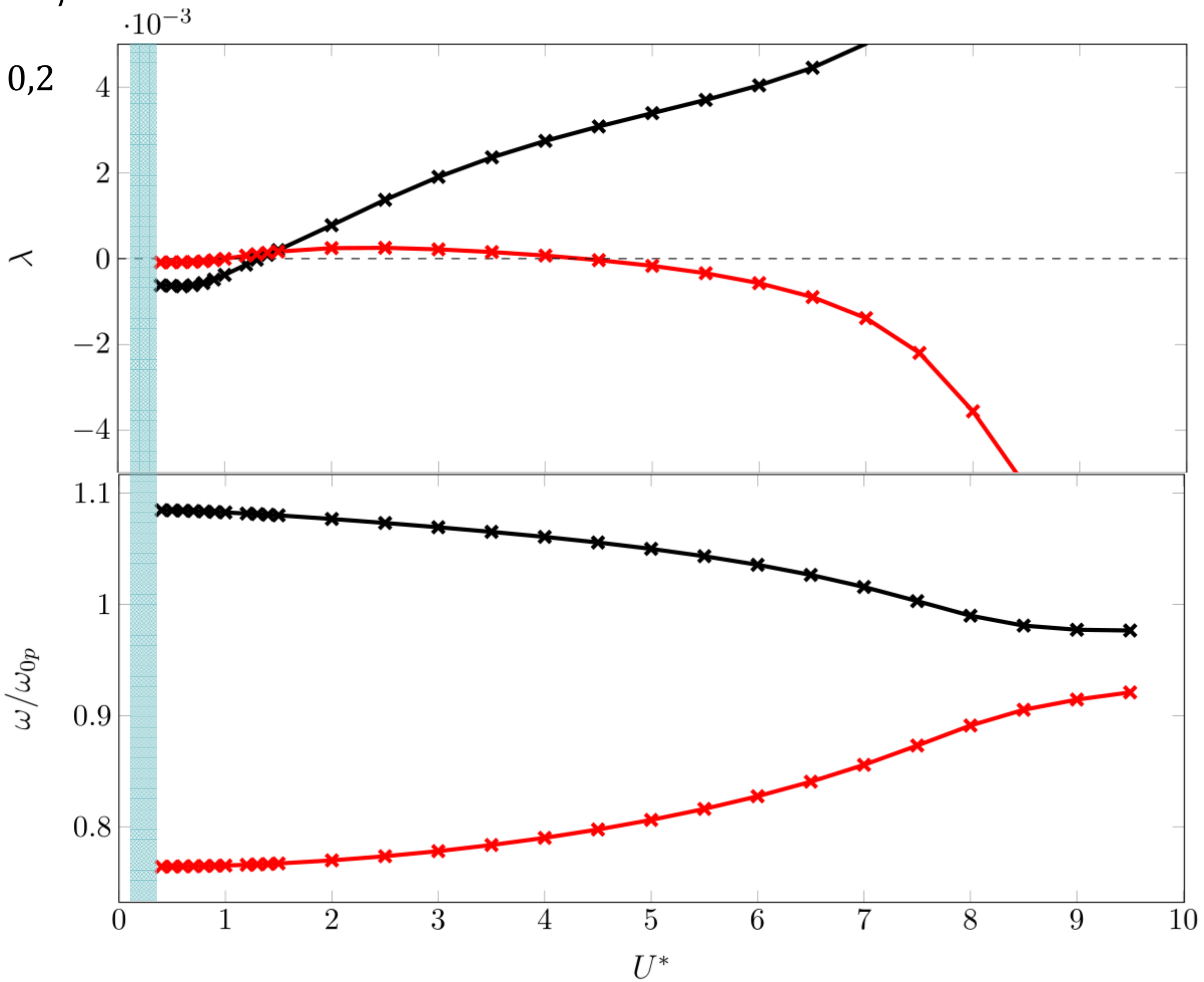
ONERA

THE FRENCH AEROSPACE LAB

Aeroelastic instabilities of a 2-DOF short plate

VIV
(not investigated here)

$$U^*_{VIV} \simeq \frac{1}{2\pi \, St_H \, AR} \simeq 0{,}2$$

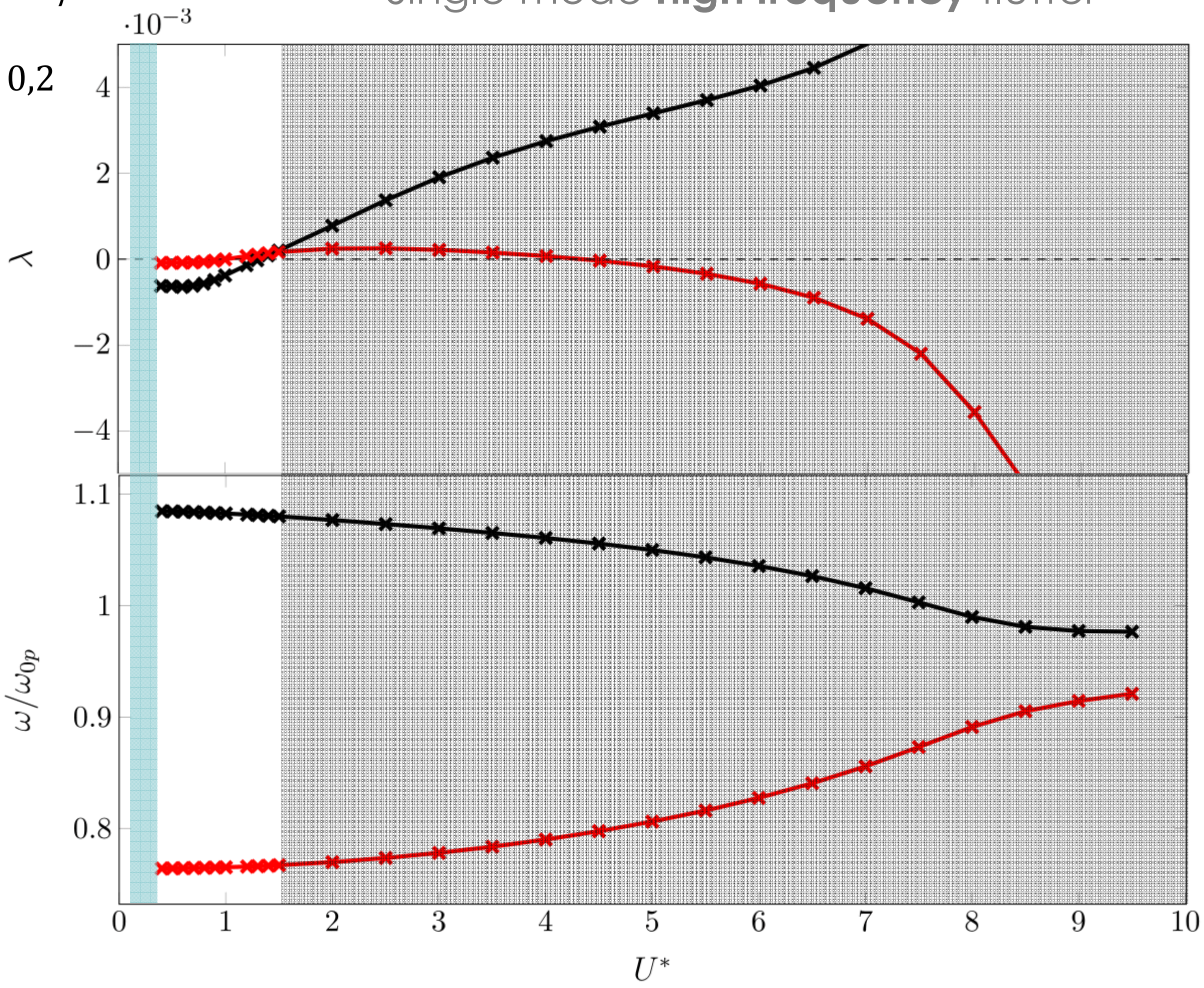


Aeroelastic instabilities of a 2-DOF short plate

VIV
(not investigated here)

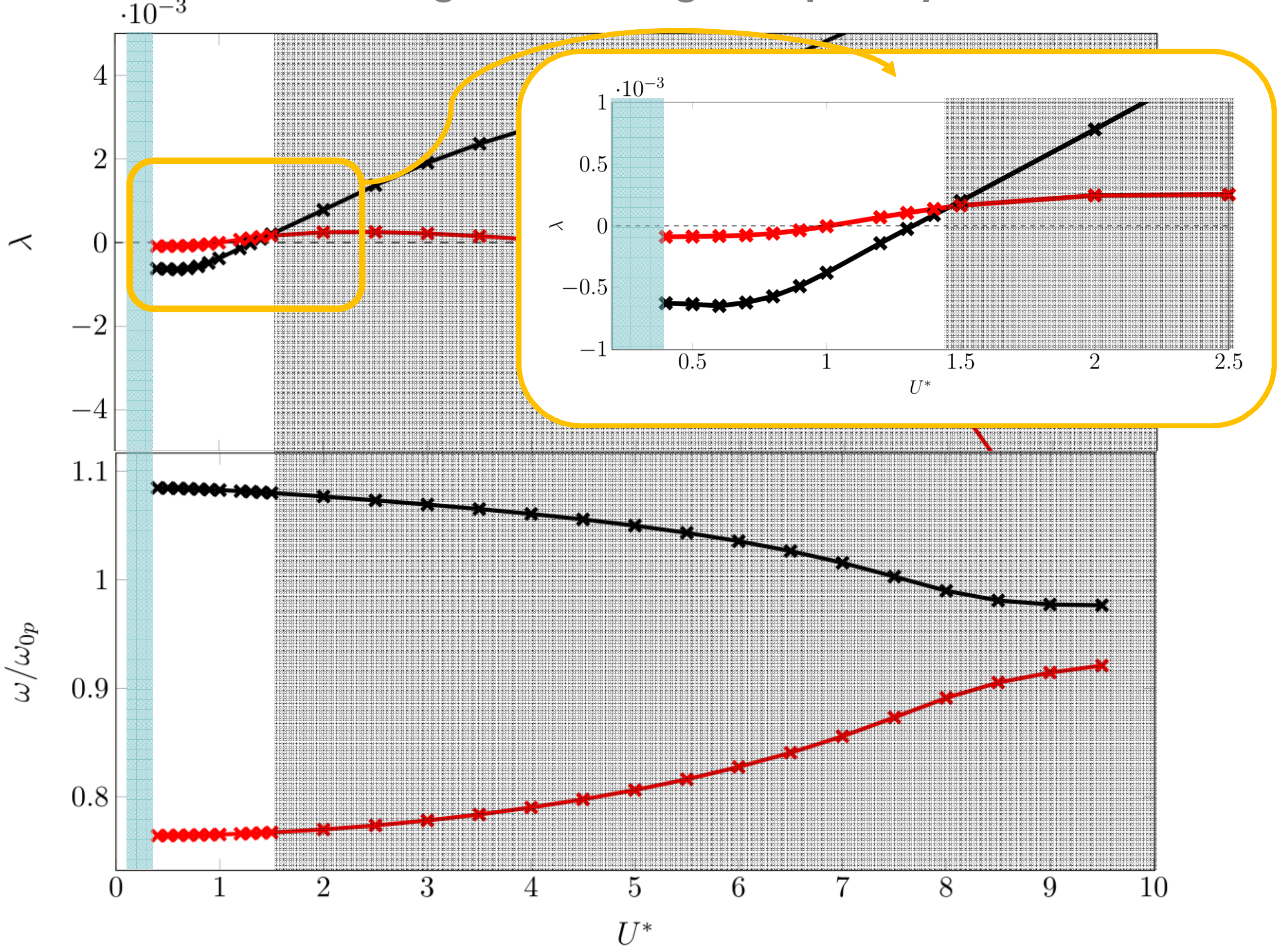
$$U^*_{VIV} \simeq \frac{1}{2\pi\, St_H\, AR} \simeq 0{,}2$$

Single mode **high frequency** flutter



Aeroelastic instabilities of a 2-DOF short plate

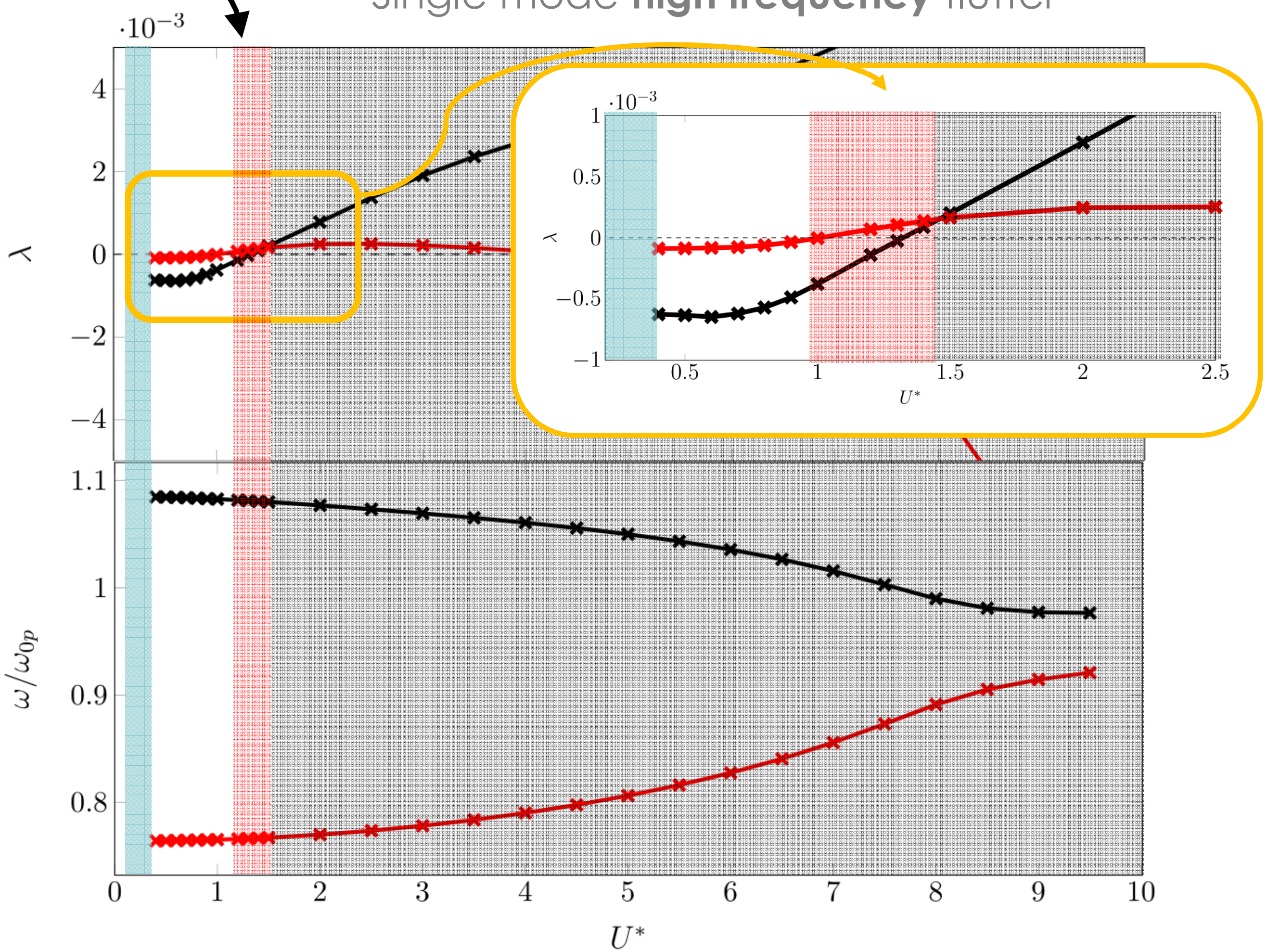
Single mode **high frequency** flutter



Aeroelastic instabilities of a 2-DOF short plate

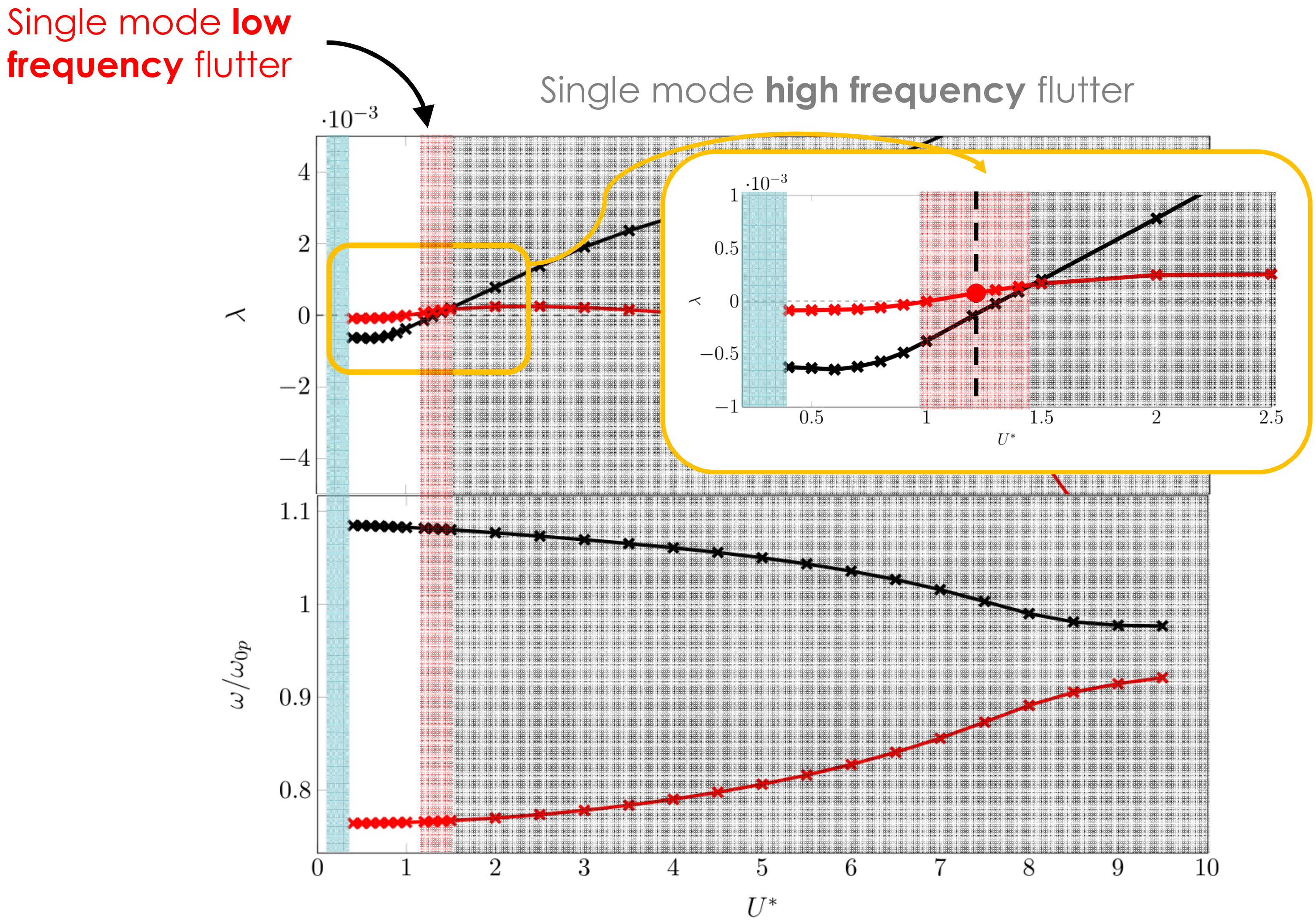
Single mode **low frequency** flutter

Single mode **high frequency** flutter



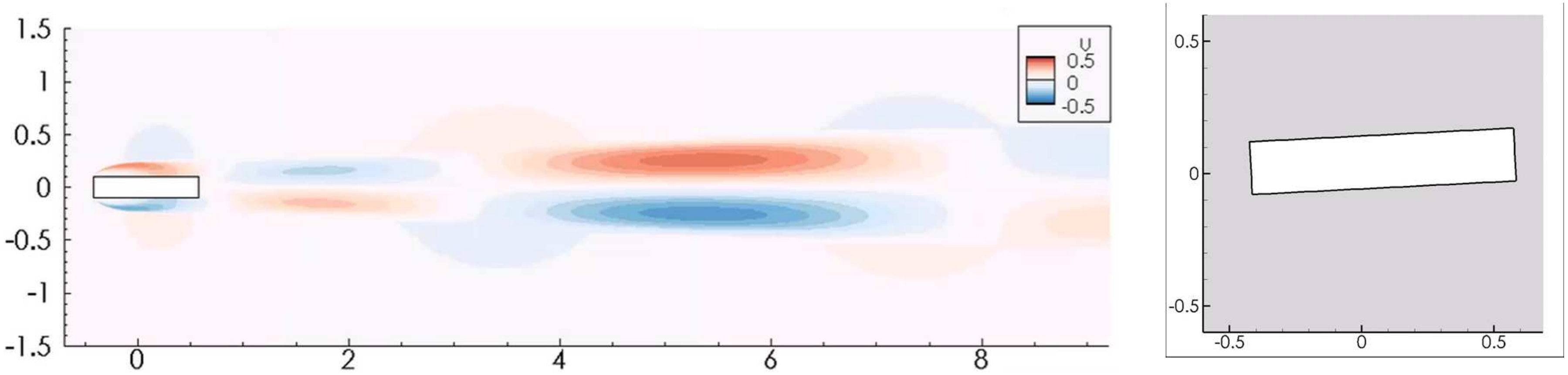
ONERA
THE FRENCH AEROSPACE LAB

Aeroelastic instabilities of a 2-DOF short plate



ONERA
THE FRENCH AEROSPACE LAB

Aeroelastic instabilities of a 2-DOF short plate

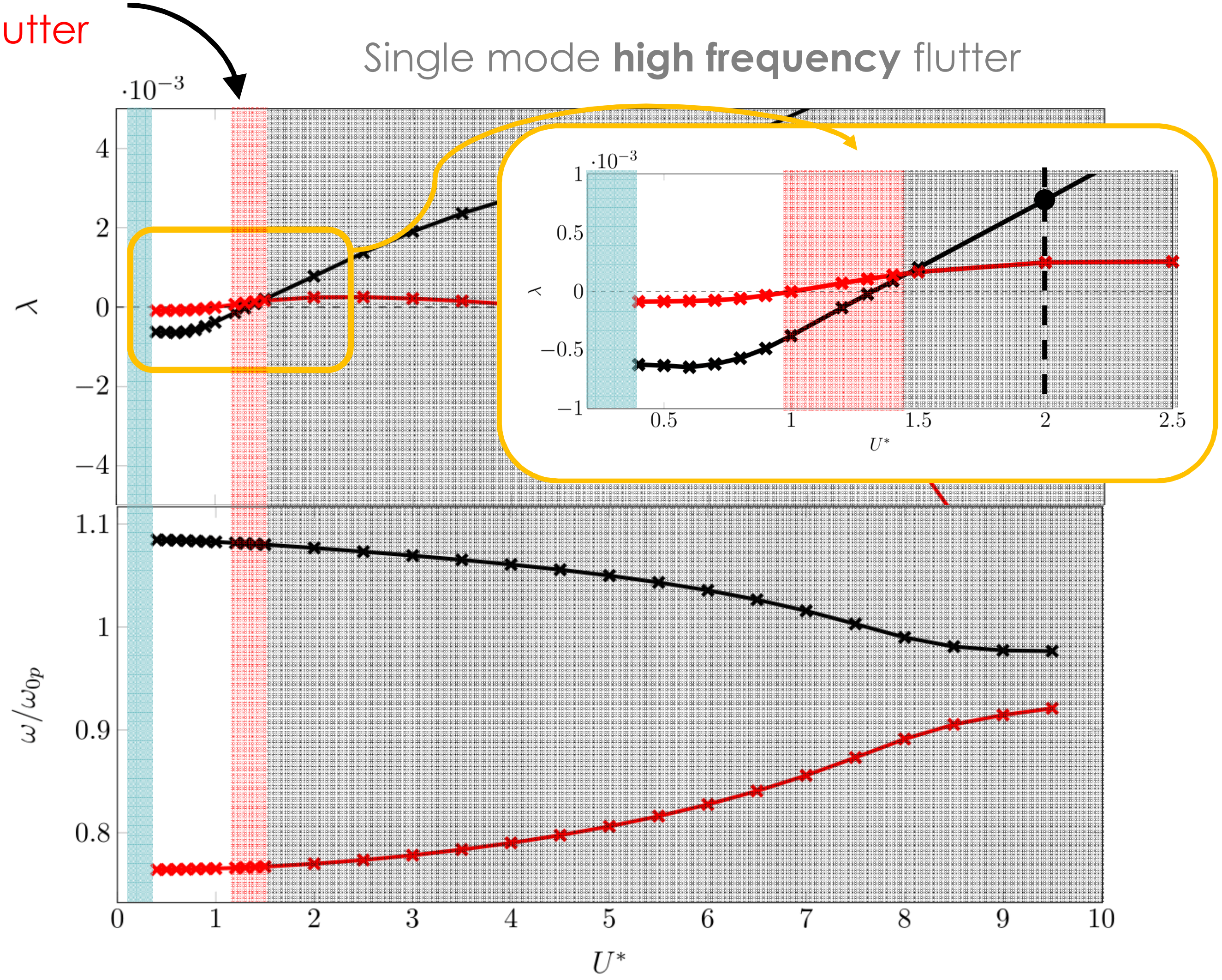


Low frequency flutter mode

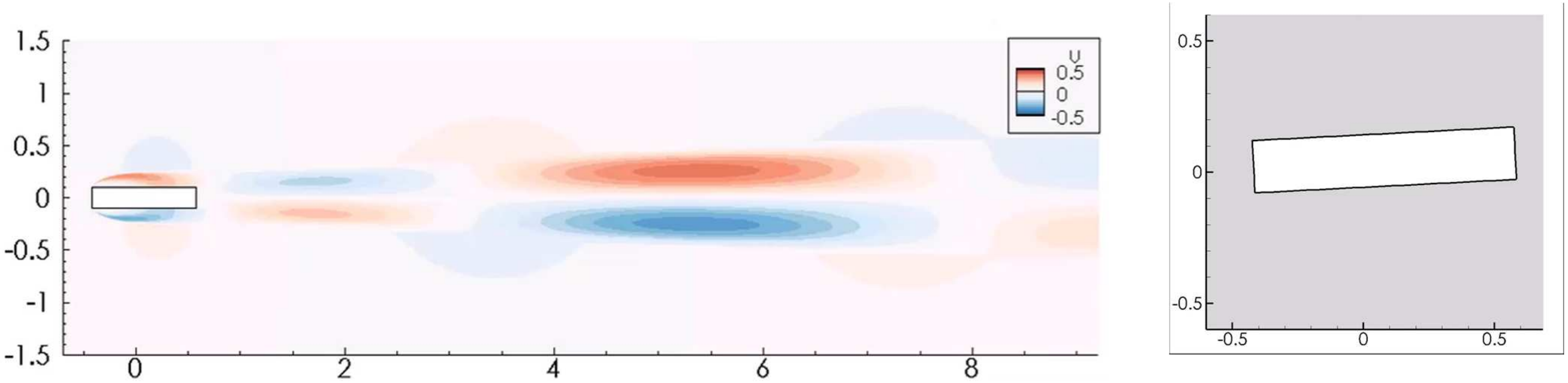
Aeroelastic instabilities of a 2-DOF short plate

Single mode **low frequency** flutter

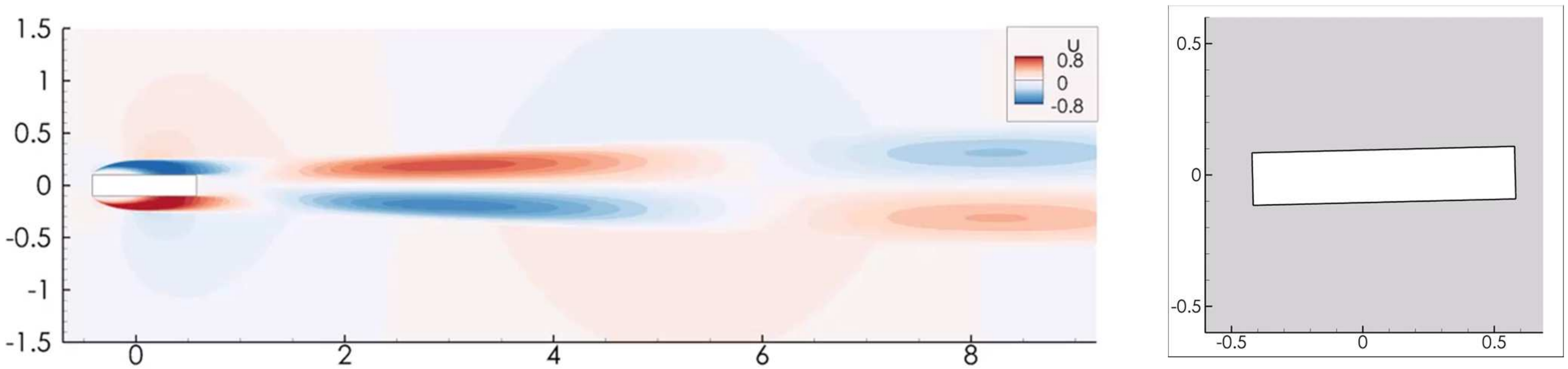
Single mode **high frequency** flutter



Aeroelastic instabilities of a 2-DOF short plate



Low frequency flutter mode



High frequency flutter mode

Comparison to Theodorsen …

	U^*_{crit}	ω/ω_{0p}
Present study (low frequency branch)	**0,98**	**0,77**
Present study (high frequency branch)	**~1,4**	**1,08**
Theodorsen	4,3	1,03

- Clear difference bewteen RANS and Theodorsen
- Well known phenomena : **single-mode flutter** is **difficult to model**
  - Neither Theodorsen nor other simple method work

✓ **Interest of using a full RANS modelling**

Conclusions :

- **Single-mode and coupled-mode flutter in turbulent flow** have been investigated through **global linear stability analysis …**
  - Streamlined body : coupled-mode flutter
  - Bluff body : single-mode flutter
- A **full RANS modelling** of the fluid has been used
- The role of recirculation areas in stability has been discussed
  - Theodorsen's model can be extended to the case of limited detached areas

Conclusion & Perspectives

Perspectives :

- Experimental results on the case $AR = 5$ for validation
- Consider flexible structures
- 3D configurations
- Towards stabilization strategies of those unstable modes