Symmetry breaking of rigid or flexible splitter plate in a cylinder wake

Marie Couliou, Remi Allandrieu, Jean-Lou Pfister and Olivier Marquet
DAAA/ONERA, Meudon, France
marie.couliou@onera.fr

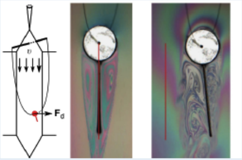
Funding: AEROFLEX - ERC Starting Grant (2014)

8th International Symposium on Bifurcations and Instabilities in Fluid Dynamics
July 17, 2019
University of Limerick, Ireland

ONERA
THE FRENCH AEROSPACE LAB

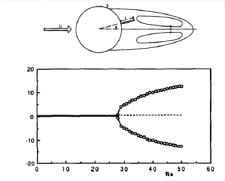
Spontaneous deviations in fluid/solid systems

Low-Re flow, freely rotating plate



Lacis *et al.*, Nature, 2014

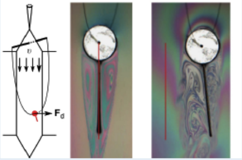
Low-Re flow, freely rotating plate (numerical study)



Xu *et al.*, Phys. Fluids, 1990

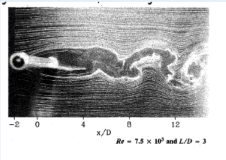
Spontaneous deviations in fluid/solid systems

Low-Re flow, freely rotating plate



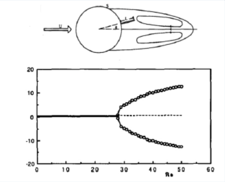
Lacis *et al.*, Nature, 2014

Higher-Re flow, freely rotating plate



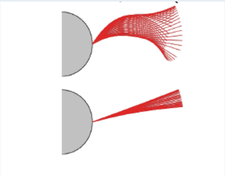
Cimbala and Garg, AIAA, 1991

Low-Re flow, freely rotating plate (numerical study)



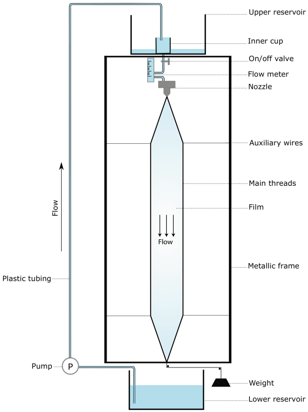
Xu *et al.*, Phys. Fluids, 1990

Clamped flexible plate (numerical study)



Bagheri *et al.*, Phys. Rev. Lett., 2012

Experimental setup - Soap film channel and visualisation



Test section [1]

- Dimension : 90 $cm * 9$ cm
- Flowing fluid film ($< 10\mu m$)
- $U = 2.2m/s$

Visualisation - Lightning

- Thin-film interference [2]
- Monochromatic light : green LED 535nm
- White polychromatic light

Visualisation - Acquisition

- Camera : Phantom 7.3 : $F_a = 4000$ Hz

[1] Rutgers *et al.*, RS Inst., 72 (7) (2001)
[2] Gharib and Beizaie of Visualization 2, 119-126 (1999)

Experimental setup

- Cylinder : $D = 3\ mm$, $Re_D = 350$
- Filament : $L/D = [0 - 9]$, $E = 2\ GPa$

$L/D = 0$

Experimental setup

- Cylinder : $D = 3\ mm$, $Re_D = 350$
- Filament : $L/D = [0 - 9]$, $E = 2\ GPa$

$L/D = 0$

$L/D = 0.35$

Experimental setup

- Cylinder : $D = 3\ mm,\ Re_D = 350$
- Filament : $L/D = [0-9],\ E = 2\ GPa$

$L/D = 0$

$L/D = 0.35$

$L/D = 1.40$

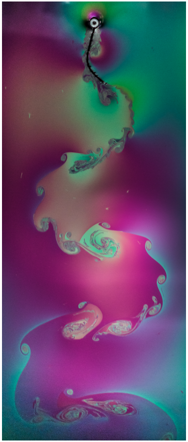
Experimental setup

- Cylinder : $D = 3\ mm$, $Re_D = 350$
- Filament : $L/D = [0 - 9]$, $E = 2\ GPa$

$L/D = 0$

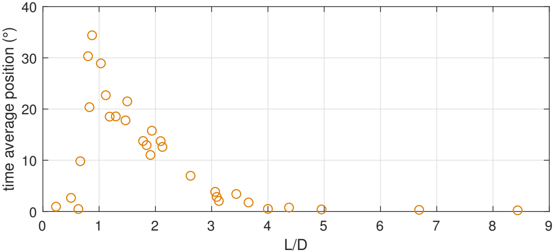
$L/D = 0.35$

$L/D = 1.40$

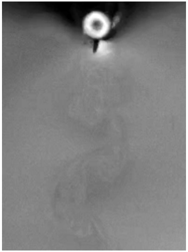


$L/D = 6.89$

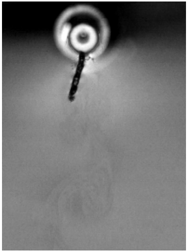
Experimental results - Static instability



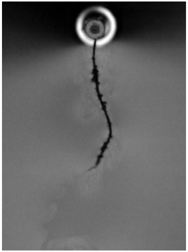
L/D=0.7



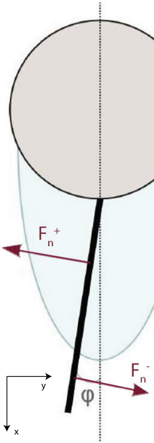
L/D=1.8



L/D=8.4



Simplified theoretical model



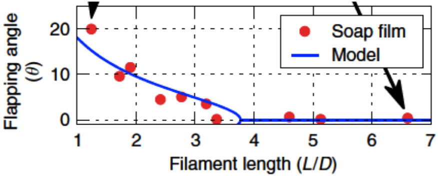
Fluid forces [1]

- Fluid force inside the back flow

$$F_n^+ = \mathcal{A}B\left(-U_{bf} + \frac{B}{2}\dot{\phi}sin(\phi)\right)^2 sin(\phi)$$

- Fluid force outside the back flow

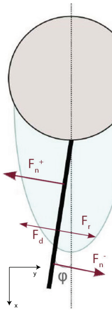
$$F_n^- = -\mathcal{A}\left(L-B\right)\left(U_f + \frac{L+B}{2}\dot{\phi}sin(\phi)\right)^2 sin(\phi)$$



[1] Lacis, et al, Nature, 2014

ONERA THE FRENCH AEROSPACE LAB

Theoretical model



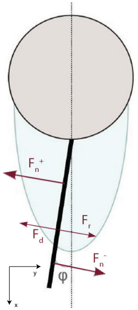
Filament drag force $\implies$ Moment opposed to filament motion

$$F_d = \pm \mathcal{A}\, L \left(\frac{L}{2} \dot{\phi} \right)^2$$

Stiffness restoring force $\implies$ Stabilising moment

$$F_r = -\frac{1}{2} K L \sin(\phi)$$

Theoretical model



Filament drag force $\Longrightarrow$ Moment opposed to filament motion

$$F_d = \pm \mathcal{A}\, L \left(\frac{L}{2}\dot{\phi}\right)^2$$

Stiffness restoring force $\Longrightarrow$ Stabilising moment

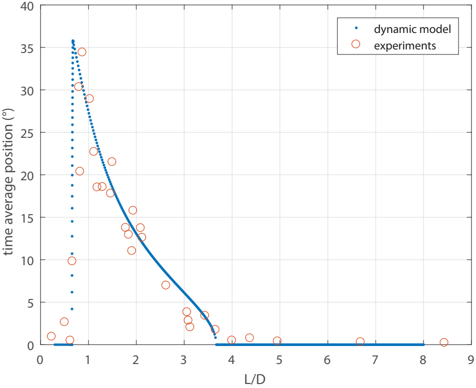
$$F_r = -\frac{1}{2} K L \sin(\phi)$$

Moment equation

At the filament hinge point, projected along the filament axis :

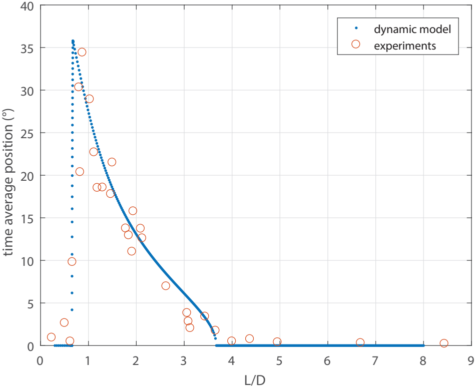
$$\ddot{\phi} = \frac{1}{I_0}\left(F_n^+\left[\frac{B}{2}\right] + F_n^-\left[\frac{B}{2}+\frac{L}{2}\right] + F_r\left[\frac{2L}{3}\right] + F_d\left[\frac{2L}{3}\right]\right)$$

Theoretical model - Results : static instability



$L < 0.65D$
$\phi = 0$ **stable**

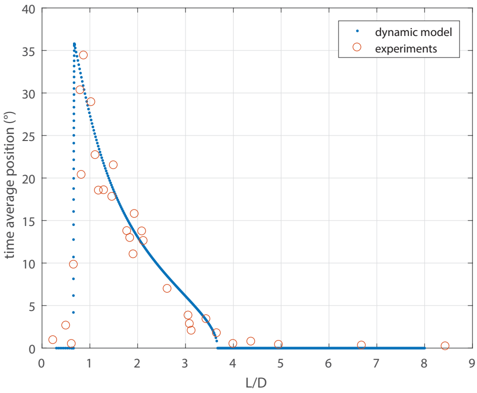
Theoretical model - Results : static instability



$L < 0.65D$
$\phi = 0$ **stable**

$0.65D < L < 3.6D$
$\phi > 0$ **unstable**

Theoretical model - Results : static instability



$L < 0.65D$
$\phi = 0$ **stable**

$0.65D < L < 3.6D$
$\phi > 0$ **unstable**

$3.6D < L$
$\phi = 0$ **stable**

Derivation of the mode

Dynamics of the solid is described with only one time-dependent variable $\alpha(t)$,

Solid displacement field :

$$\vec{\xi}(\vec{x}, t) \simeq \alpha(t)\vec{\phi}(\vec{x})$$

with $\vec{\phi}(\vec{x})$: first bending mode of the solid.

Projection of the fluid-solid dynamics on this vibration mode

$$M\frac{\mathrm{d}^2\alpha}{\mathrm{d}t^2} + K(E_s)\,\alpha = F(t, \alpha) \tag{1}$$

with M : the modal mass coefficient, K : modal stiffness coefficient, F : modal projection of the aerodynamic forces

Derivation of the mode

Hypotheses : 2 time scales + Taylor decomposition

$$\left.\frac{\mathrm{d} < F >}{\mathrm{d}\alpha}\right|_0 \simeq \underbrace{\left\{\frac{1}{\varepsilon}\int_{\Gamma(\varepsilon)} < \boldsymbol{\sigma}(\boldsymbol{u},\boldsymbol{p})\boldsymbol{n} > \cdot\boldsymbol{\phi}\,\mathrm{d}\Gamma\right\}}_{\delta F}\alpha$$

with $< \boldsymbol{\sigma}(\boldsymbol{u},\boldsymbol{p})\boldsymbol{n} >$: mean aerodynamic load

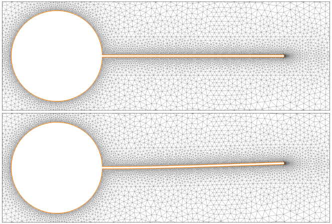
$$M\frac{\mathrm{d}^2\alpha}{\mathrm{d}t^2} + (K(E_s) - \delta F)\,\alpha = 0. \qquad (2)$$

- quasi-static deviation appears as a divergence instability
- when the threshold $K(E_s) = \delta F$ is crossed
- i.e. when the added stiffness force generated through the interaction with the mean flow balances the restoring elastic force

Numerical methods and results

Methodology

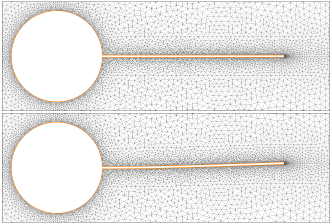
- Time-average loads exerted by the fluid on the rigid, deformed configurations extracted from time-marching simulations
- Incompressible NS equations solved using a semi-implicit solver

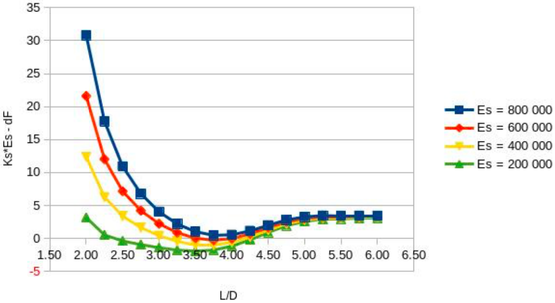


Numerical methods and results

Methodology

- Time-average loads exerted by the fluid on the rigid, deformed configurations extracted from time-marching simulations
- Incompressible NS equations solved using a semi-implicit solver





$Re = 250$

Conclusion

Experimental study

- Enlighten a bifurcation at low filament aspect ratio

Conclusion

Experimental study

- Enlighten a bifurcation at low filament aspect ratio

Phenomelogical model

- Adding stiffness restoring force
- Captures the bifurcation at low L/D
- Limitation : data-fitted parameters ...

Conclusion

Experimental study

- Enlighten a bifurcation at low filament aspect ratio

Phenomelogical model

- Adding stiffness restoring force
- Captures the bifurcation at low L/D
- Limitation : data-fitted parameters ...

Quasi-steady model

- The 2 bifurcations are captured
- At Re=250, thresholds not the same as in the experiments
- Simulations at experimental Re=350 are ongoing ...

Thank you for you attention