PIV-based estimation of unsteady loads on a flat plate at high angle of attack using momentum equation approaches

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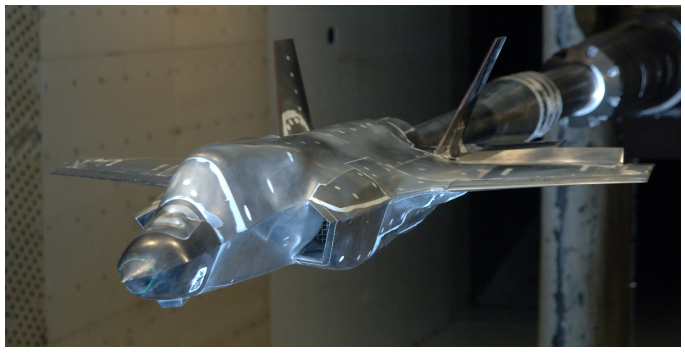
[2]Department of Aerospace Engineering, University of Michigan

APS-DFD - 23rd of November 2015

Motivation

Forces measurement using load sensor



Not always possible

- Moving body with high inertia
- Small forces

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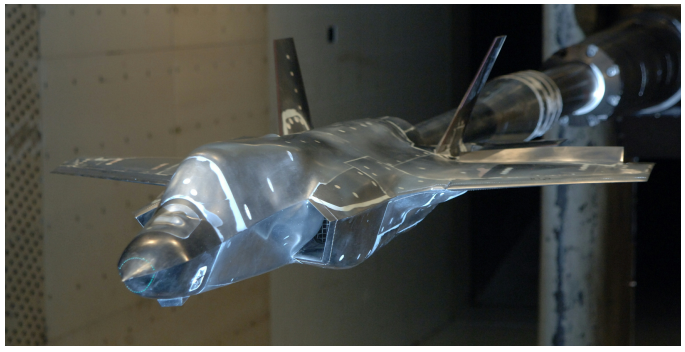


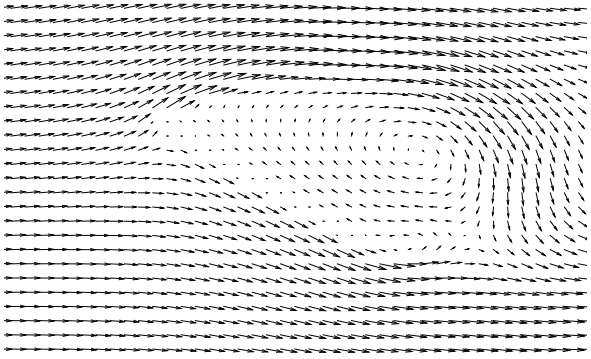
Not always possible

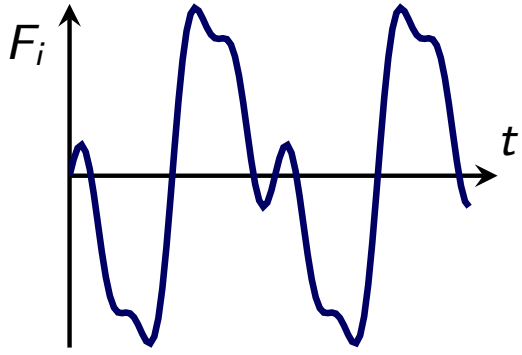
- Moving body with high inertia
- Small forces

Compute forces using PIV measurements

Objective

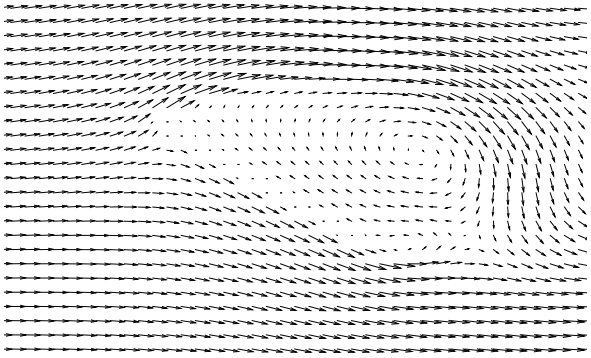
From PIV experiment → *calculate* → **Indirect calculation of forces**





Objective

From PIV experiment



Integral momentum equation

$$
\begin{aligned}
F_i = \quad & - \quad \int_{\mathcal{S}} \rho \partial_t u_i \mathrm{d}\mathcal{S} \\
& - \quad \int_{\mathcal{C}} \rho u_i \left(u_j n_j\right) \mathrm{d}\mathcal{C} \\
& - \quad \int_{\mathcal{C}} p n_i \mathrm{d}\mathcal{C} + \int_{\mathcal{C}} \tau_{ij} n_j \mathrm{d}\mathcal{C}
\end{aligned}
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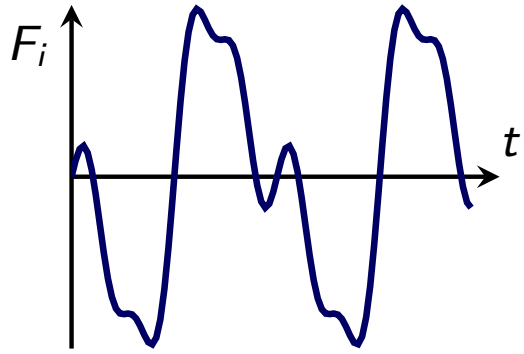
Indirect calculation of forces



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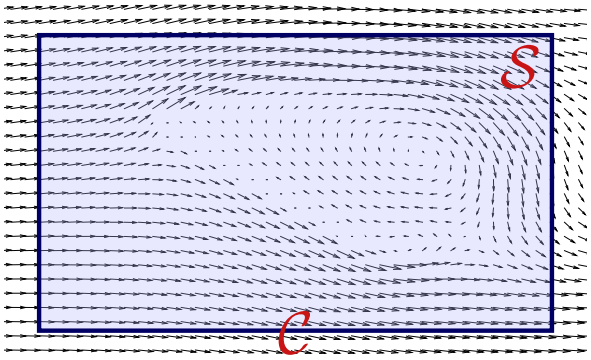
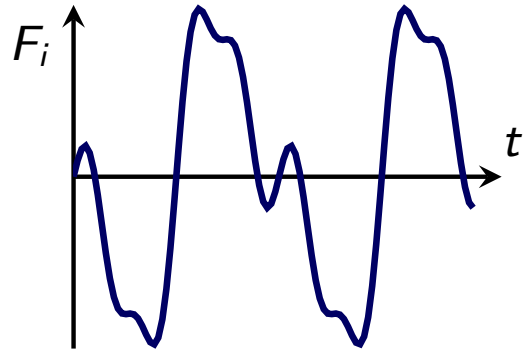


Integral momentum equation

$$F_i = - \int_{\mathcal{S}} \rho \partial_t u_i \mathrm{d}\mathcal{S} - \int_{\mathcal{C}} \rho u_i \left(u_j n_j\right) \mathrm{d}\mathcal{C} - \int_{\mathcal{C}} p n_i \mathrm{d}\mathcal{C} + \int_{\mathcal{C}} \tau_{ij} n_j \mathrm{d}\mathcal{C}$$

Indirect calculation of forces



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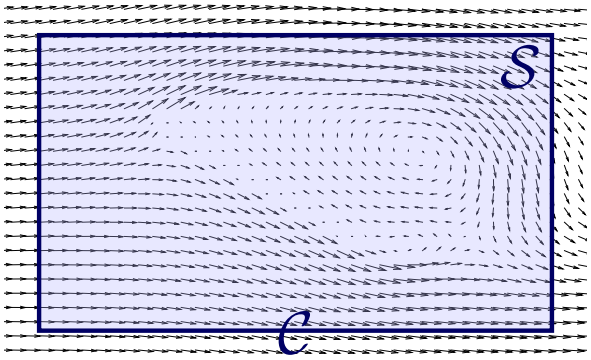

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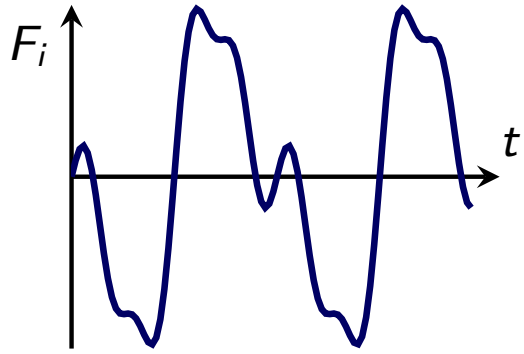

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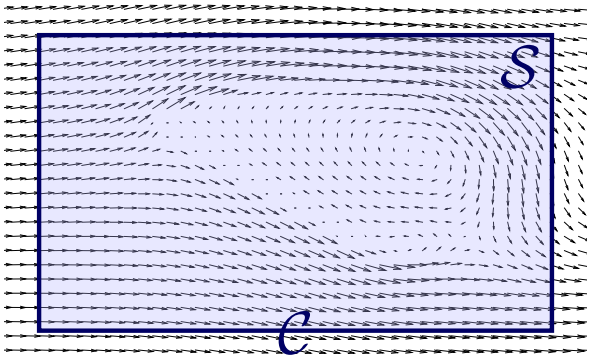

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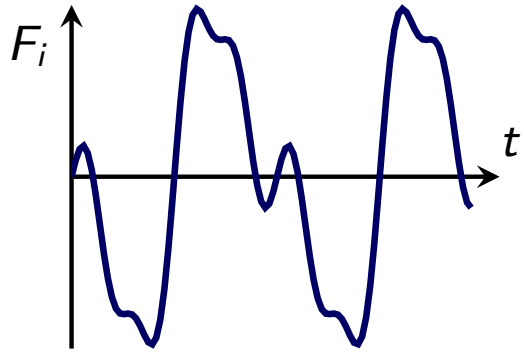

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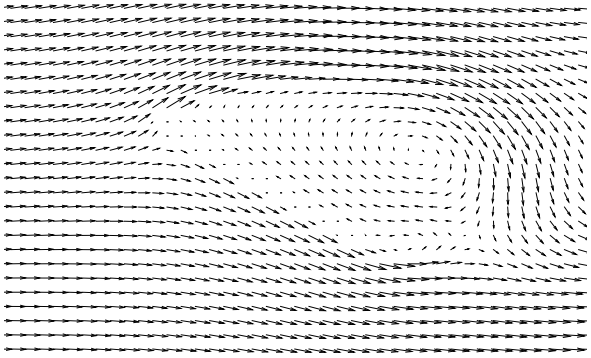

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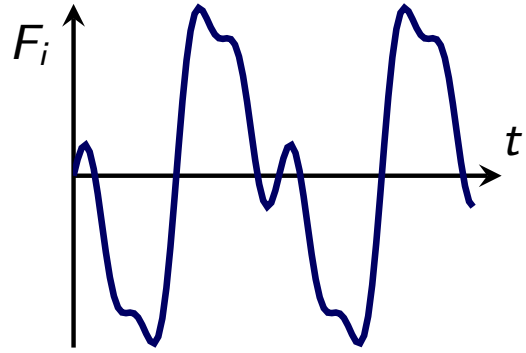

Noca's flux equation

$$
\begin{aligned}
F_i &= \int_{\mathcal{C}} n_j \gamma_{ji}^{\text{flux}} \, \mathrm{d}\mathcal{C} \\
&- \frac{\mathrm{d}}{\mathrm{d}t} \int_{\mathcal{C}_{b(t)}} \rho n_j u_j X_i \, \mathrm{d}\mathcal{C} \\
&\text{with} \\
\gamma_{ji}^{\text{flux}} &= f\left(u_i, \partial_t u_i, \partial_j u_i, X_i\right)
\end{aligned}
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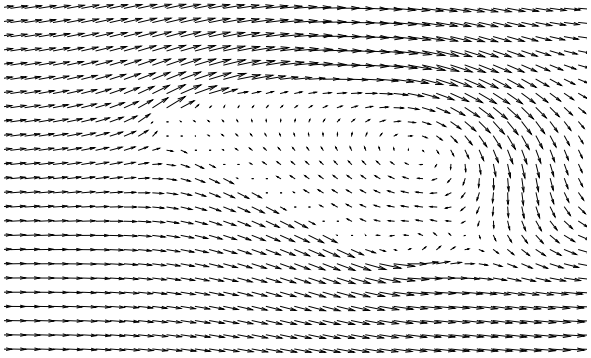
Objective

From PIV experiment



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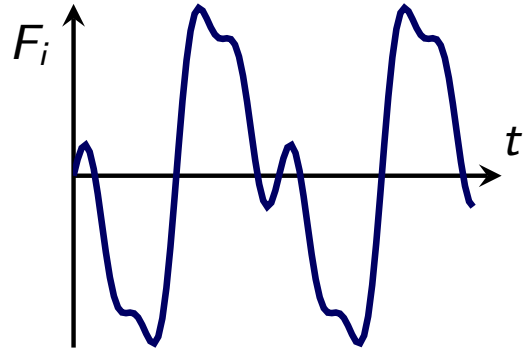

Noca's flux equation

$$F_i = \int_{\mathcal{C}} n_j \gamma_{ji}^{\text{flux}} \, \mathrm{d}\mathcal{C} - \frac{\mathrm{d}}{\mathrm{d}t} \int_{\mathcal{C}_{b(t)}} \rho n_j u_j X_i \, \mathrm{d}\mathcal{C}$$

with

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Objective

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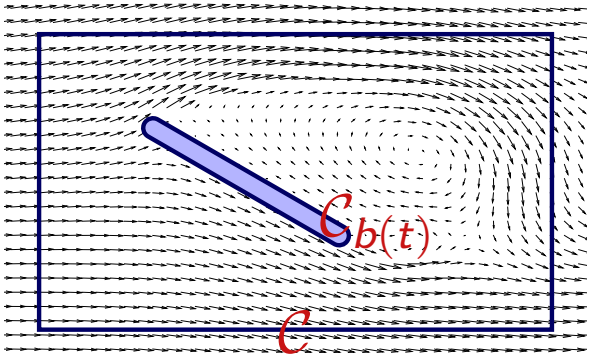

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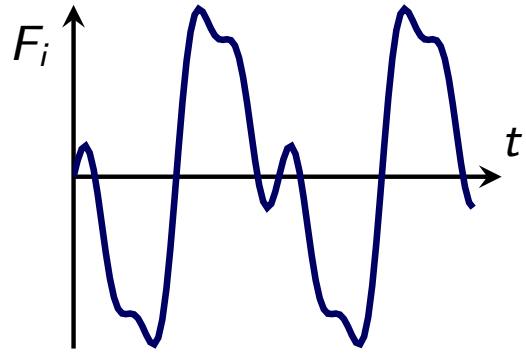

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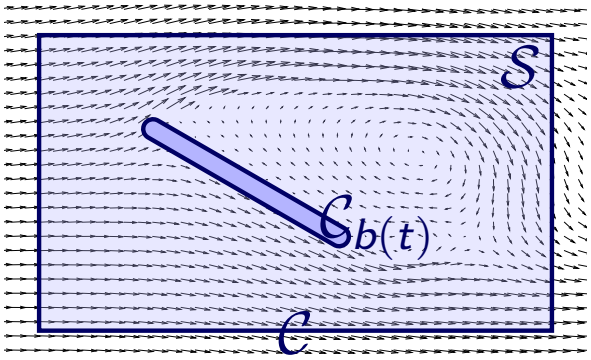

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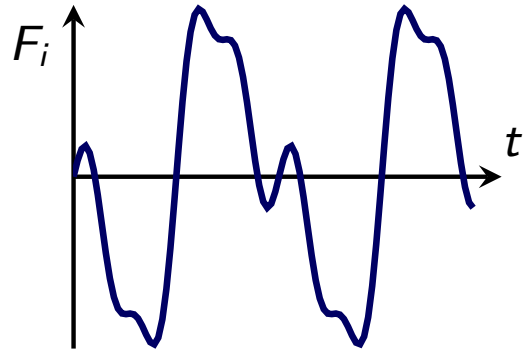

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\end{aligned}
$$

OR

Noca's flux equation

$$
\begin{aligned}
F_i \quad &= \quad \int_{\mathcal{C}} n_j \gamma_{ji}^{\text{flux}} \, \mathrm{d}\mathcal{C} \\
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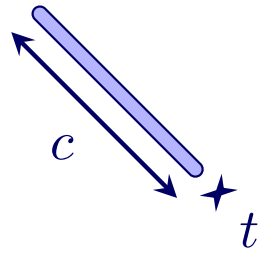
& \text{with} \\
\gamma_{ji}^{\text{flux}} \quad &= \quad f\left(u_i, \partial_t u_i, \partial_j u_i, X_i\right)
\end{aligned}
$$

Test cases

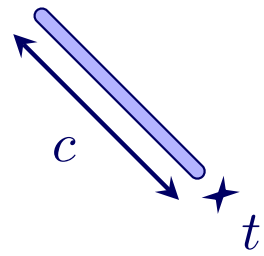
Flat plate



- $c = 7.6\text{cm}$
- $c/t = 16$
- Rounded edges

Test cases

Flat plate



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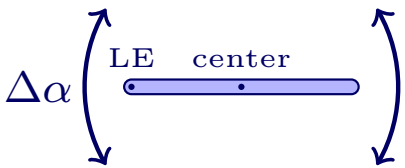
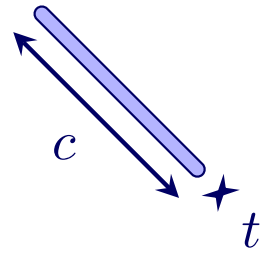
1. Large amplitude pitching



- $\overline{\alpha} = 0^\circ$
- $\Delta\alpha = 30^\circ$
- f based on $k = 0.2$
- 2 pivot axis

Test cases

Flat plate



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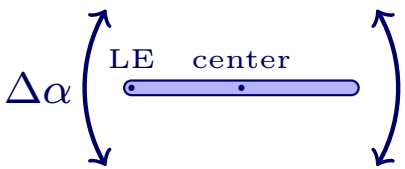
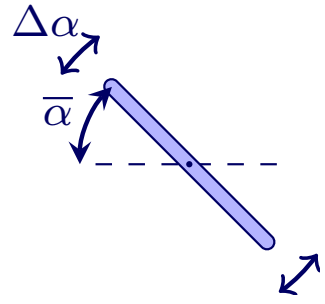


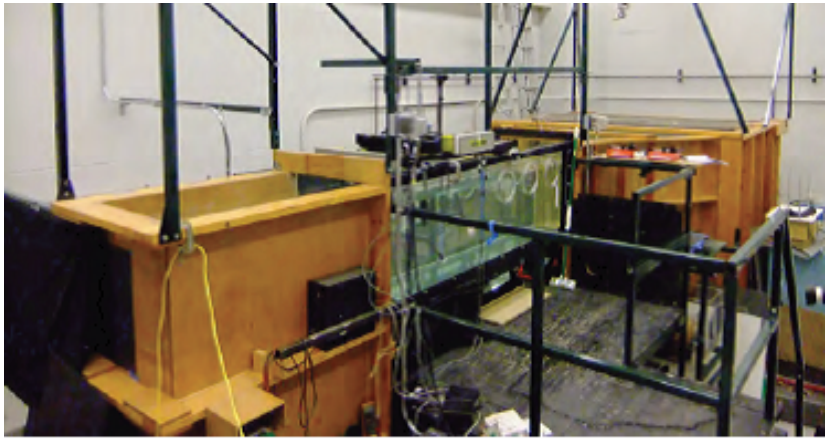
- $\overline{\alpha} = 0^\circ$
- $\Delta\alpha = 30^\circ$
- f based on $k = 0.2$
- 2 pivot axis

2. Small amplitude pitching

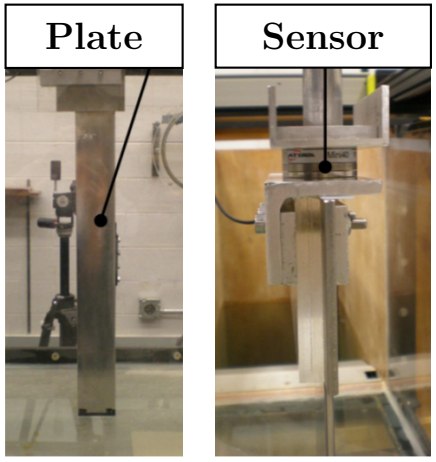


- $\alpha = \overline{\alpha} + \Delta\alpha \sin(2\pi ft)$
- $\overline{\alpha} = 45^\circ$
- f based on $St = 0.155$
- $\Delta\alpha \approx 1^\circ$

Methodology

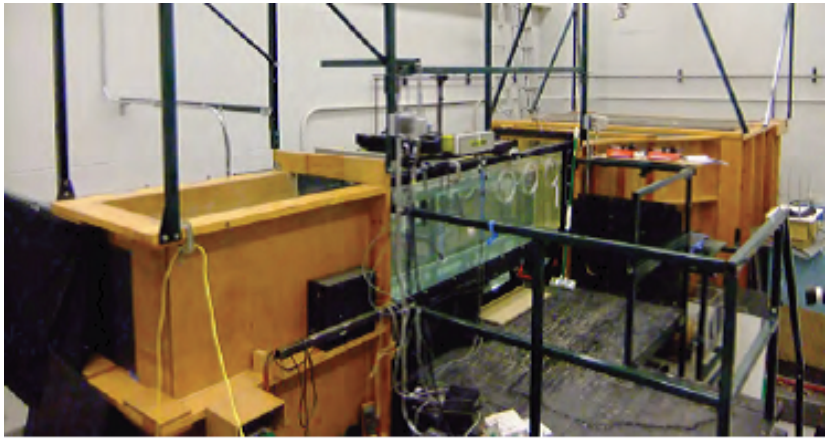


- Water channel at the University of Michigan



Data collection | **Pre-processing** | **Forces calculation**

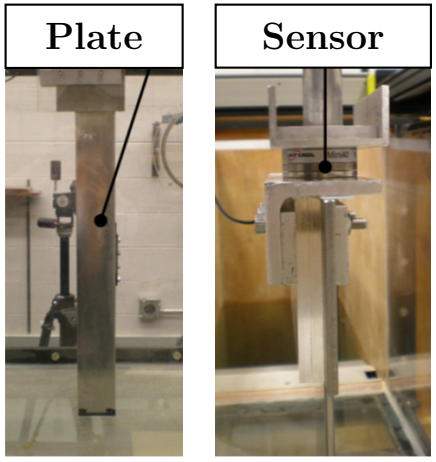
Methodology



- Water channel at the University of Michigan

$\Rightarrow$ Synchronized PIV

$\Rightarrow$ Direct force measurements



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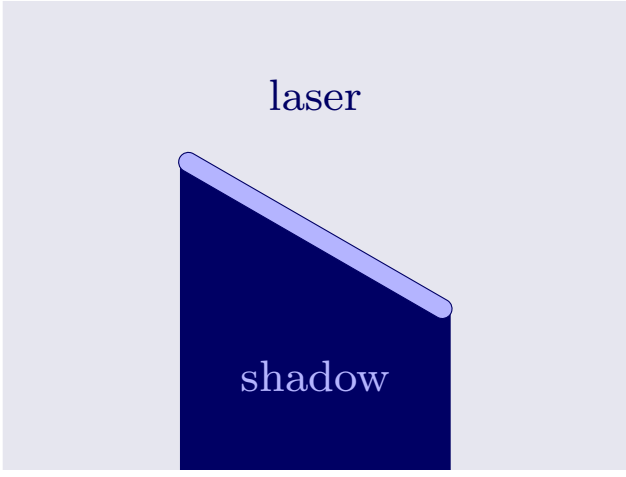
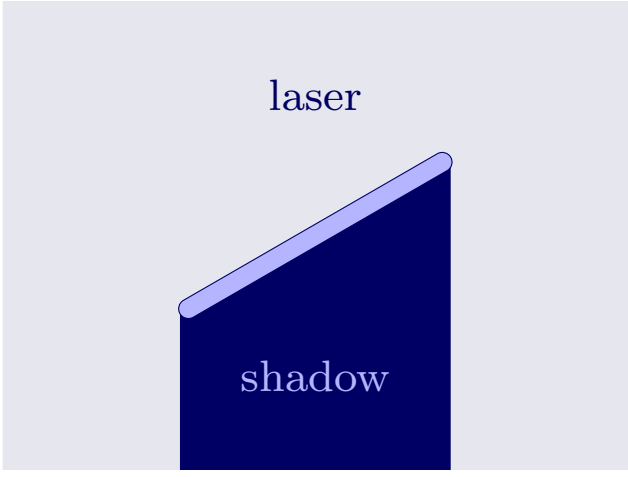


- Shadow due to mounting
- Use of symmetry
- Stitching of two images
  - $\Rightarrow$ Overlap used for stitching
  - $\Rightarrow$ But may introduce noise

Data collection → **Pre-processing** **Forces calculation**

Methodology



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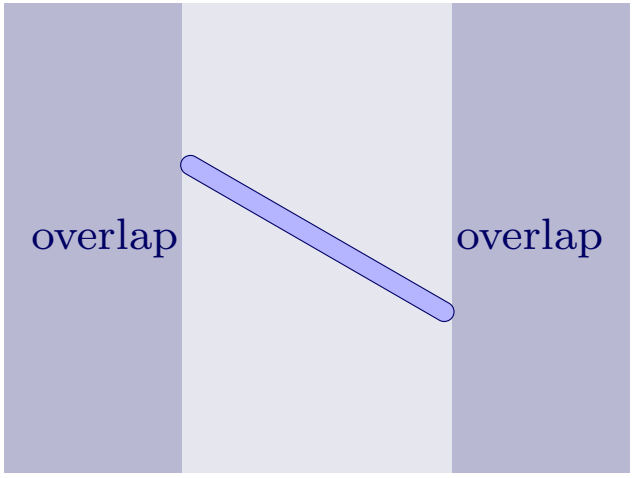

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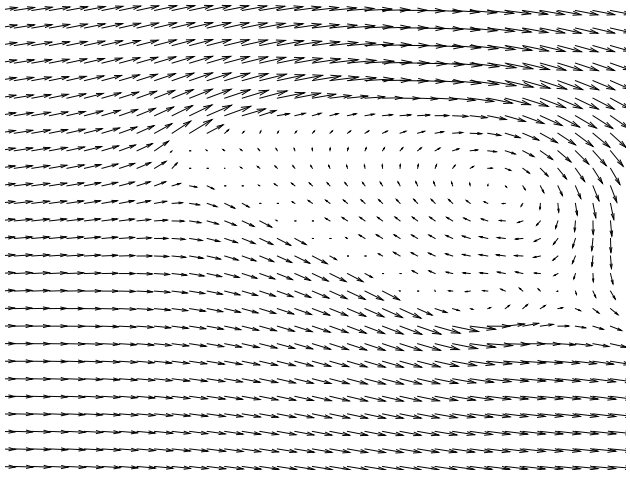

Data collection → Pre-processing → Forces calculation

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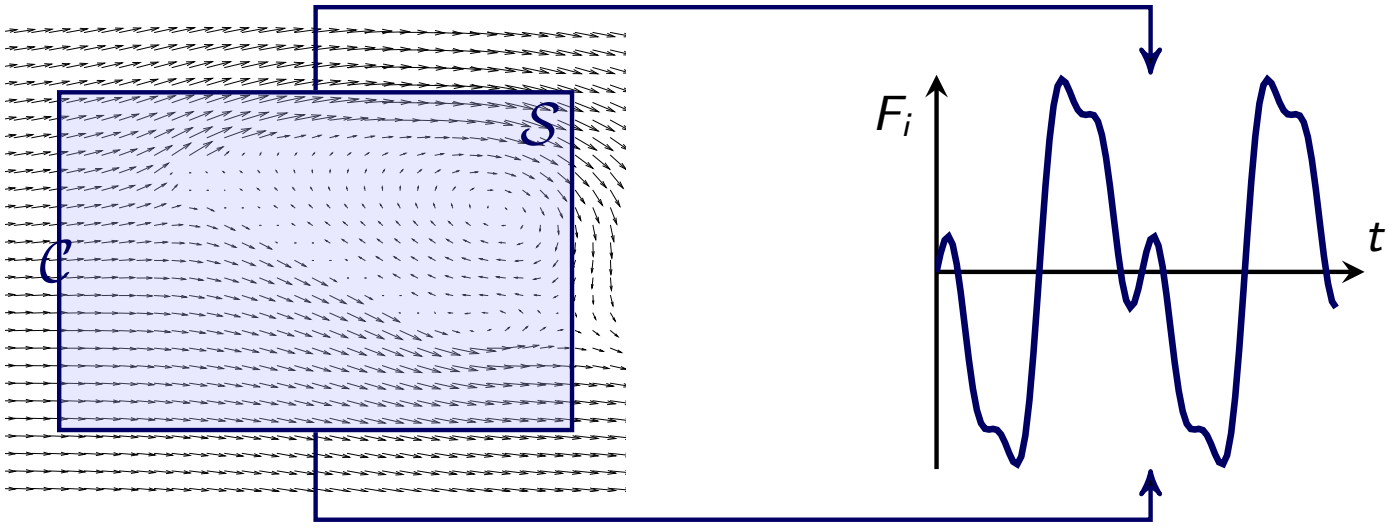

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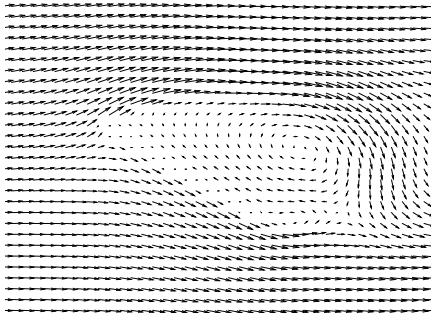
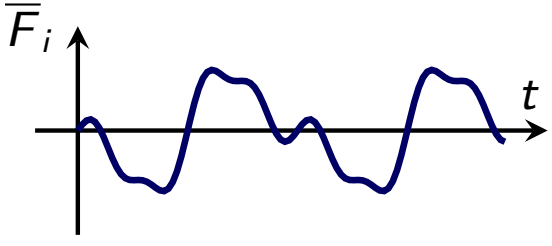
Data collection → **Pre-processing** → **Forces calculation**

Methodology: forces calculation





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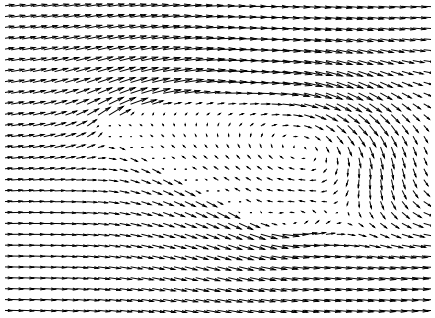
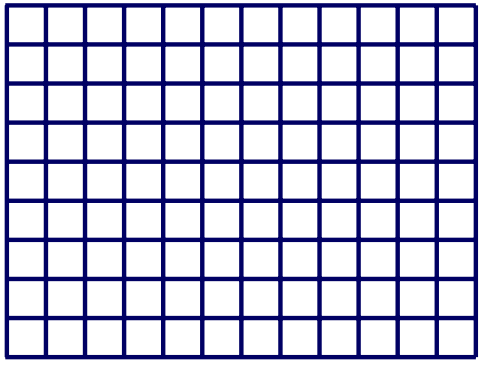
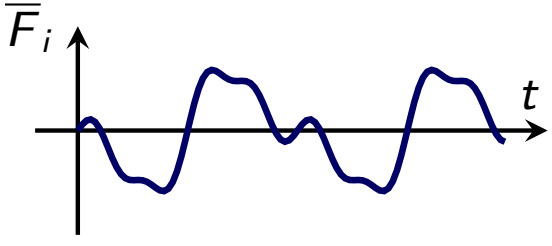


PIV data

- Phase averaging
- Definition of $\mathcal{C}$





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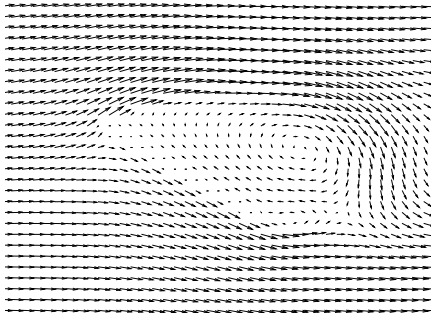

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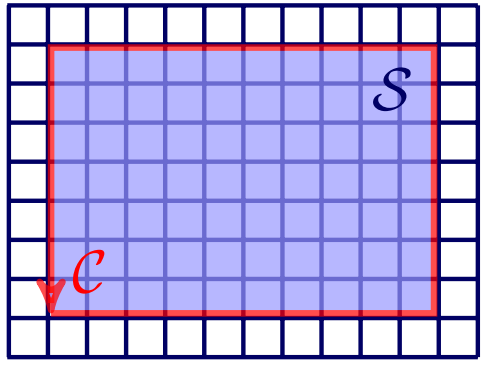
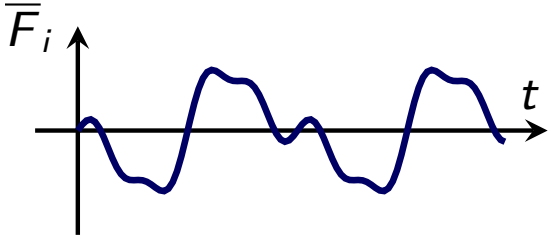
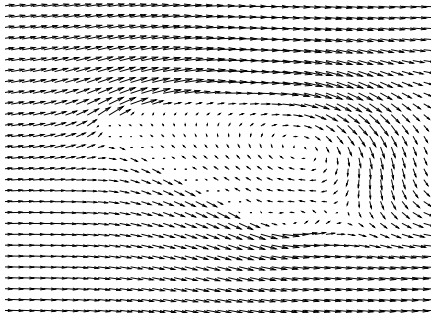




Methodology: forces calculation

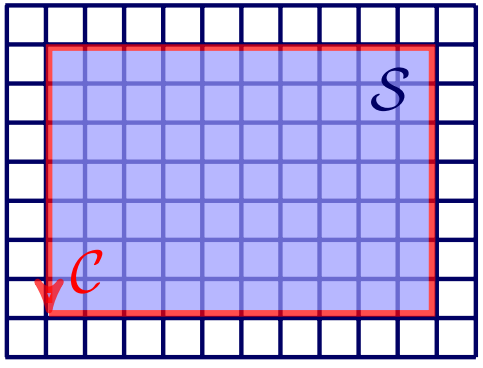


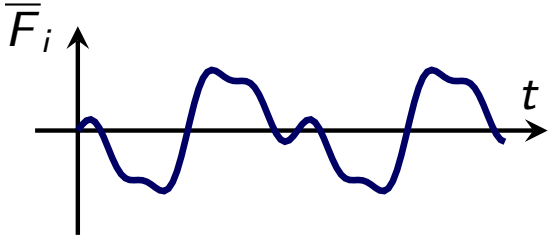
PIV data

- Phase averaging
- Definition of $\mathcal{C}$

Gradients calculation

- Finite difference





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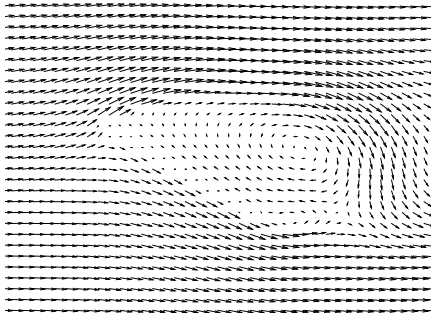

PIV data

- Phase averaging
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Gradients calculation

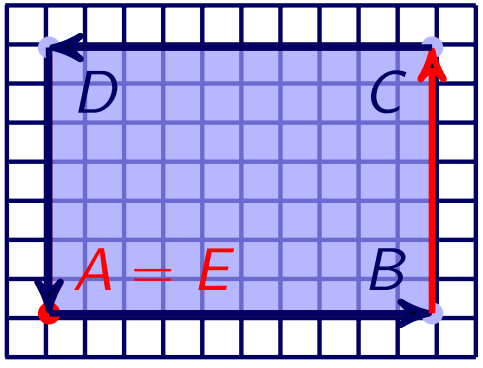
- Finite difference

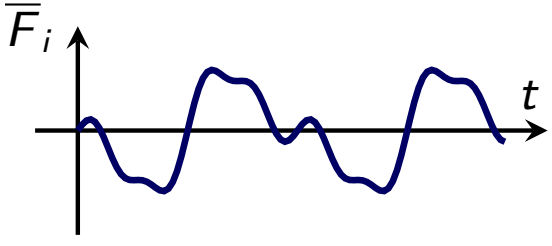
Calculation of p

- Using NS equations

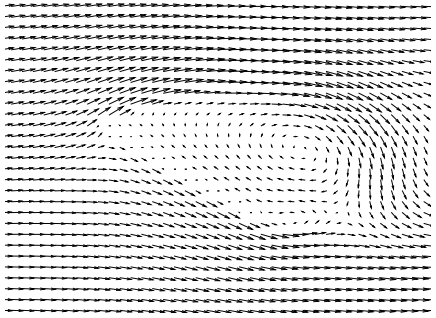
$$\partial_i \overline{p} = -\rho \partial_t \overline{u}_i - \rho \overline{u}_j \partial_j \overline{u}_i + \mu \partial^2_{jj} \overline{u}_i - \partial_j \overline{u'_i u'_j}$$

- Integration along $\mathcal{C}$





Methodology: forces calculation



PIV data

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$$\partial_i \overline{p} = -\rho \partial_t \overline{u}_i - \rho \overline{u}_j \partial_j \overline{u}_i + \mu \partial^2_{jj} \overline{u}_i - \partial_j \overline{u'_i u'_j}$$

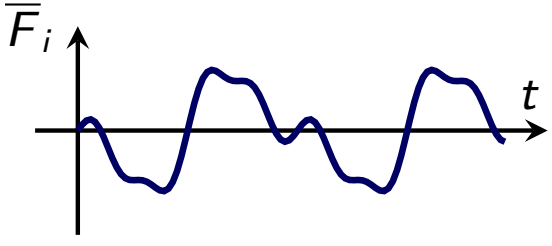
- Integration along $\mathcal{C}$

or

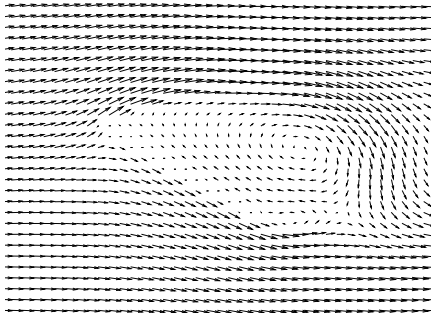
Calculation of

$$-\frac{\mathrm{d}}{\mathrm{d}t} \int_{\mathcal{C}_{b(t)}} \rho n_j \overline{u}_j X_i \, \mathrm{d}\mathcal{C}$$

- Analytical formulation



Methodology: forces calculation

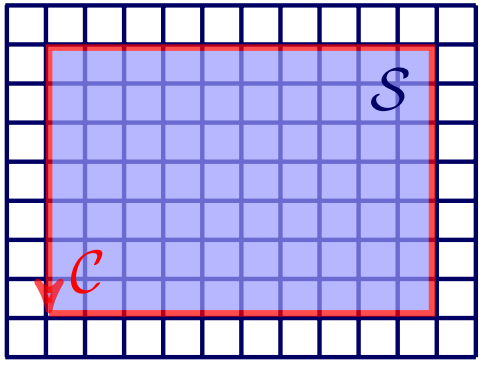


PIV data

- Phase averaging
- Definition of $\mathcal{C}$

Gradients calculation

- Finite difference



Calculation of p

- Using NS equations

$$\partial_i \overline{p} = -\rho \partial_t \overline{u}_i - \rho \overline{u}_j \partial_j \overline{u}_i + \mu \partial^2_{jj} \overline{u}_i - \partial_j \overline{u'_i u'_j}$$

- Integration along $\mathcal{C}$

or

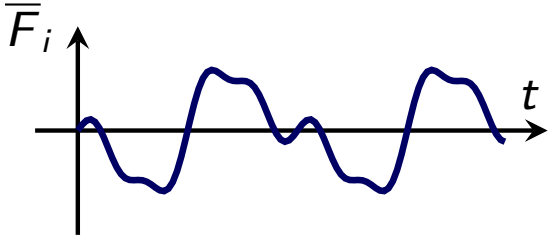
Calculation of

$$-\frac{\mathrm{d}}{\mathrm{d}t} \int_{\mathcal{C}_{b(t)}} \rho n_j \overline{u}_j X_i \, \mathrm{d}\mathcal{C}$$

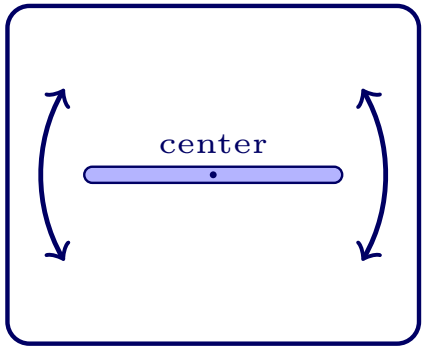
- Analytical formulation

$\overline{F}_i$ calculation

- Integration on $\mathcal{C}$ and $\mathcal{S}$



Large amplitude pitching



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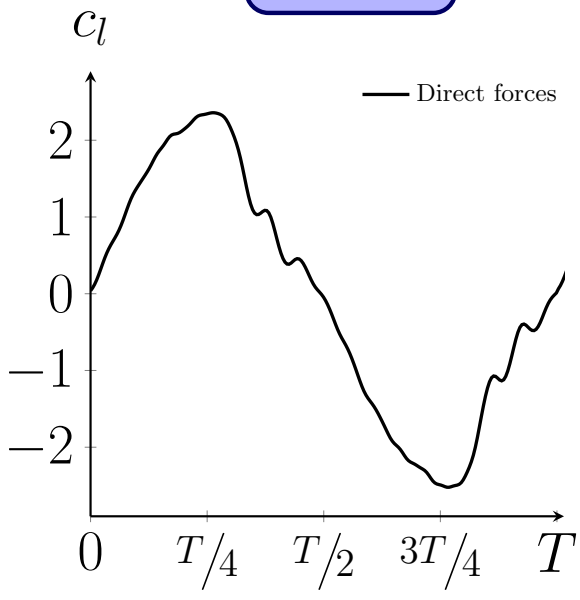

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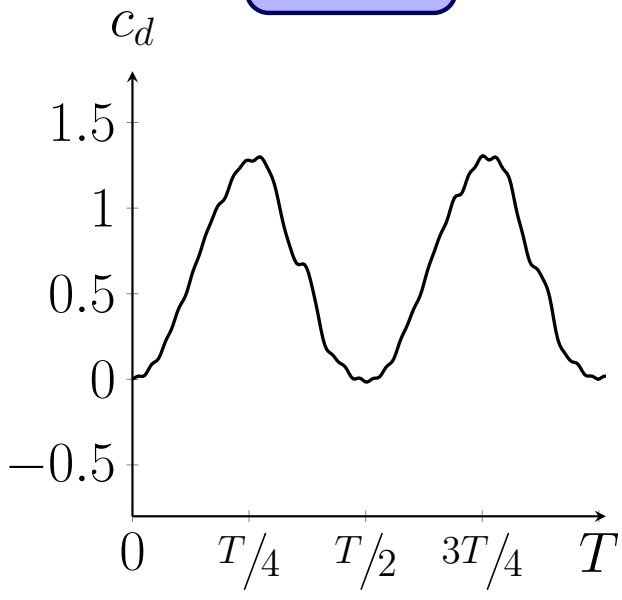
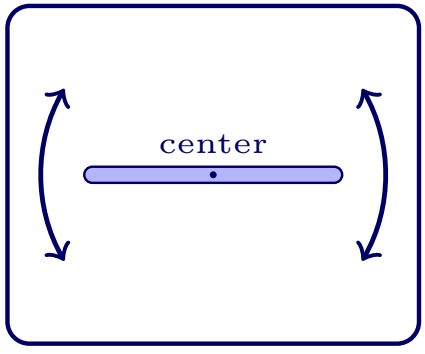


Large amplitude pitching



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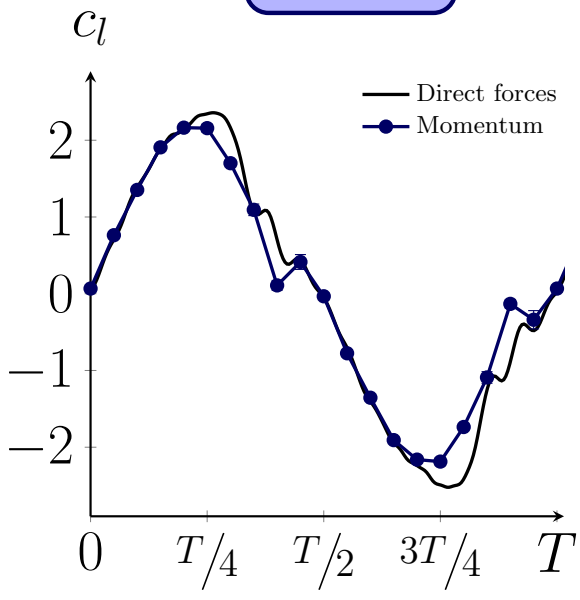

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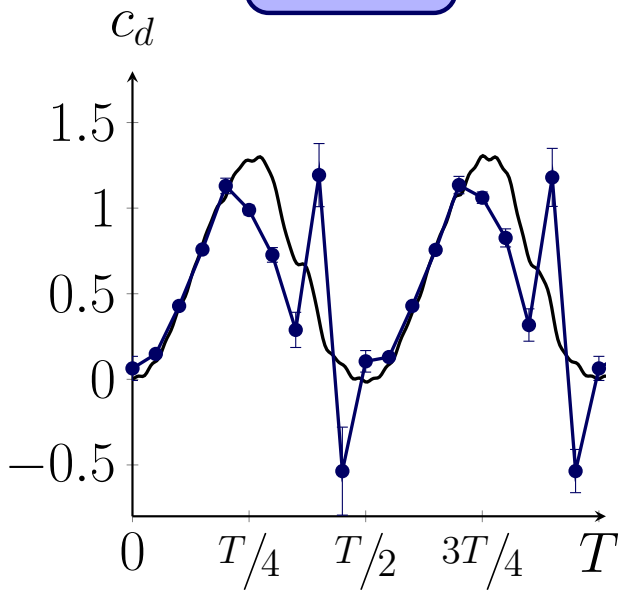

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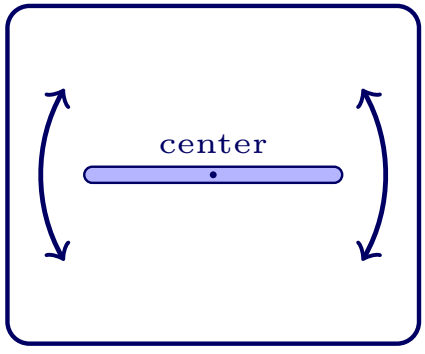

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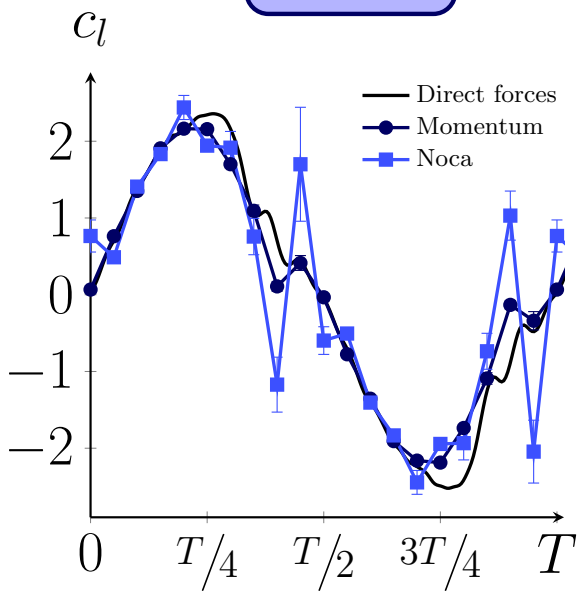

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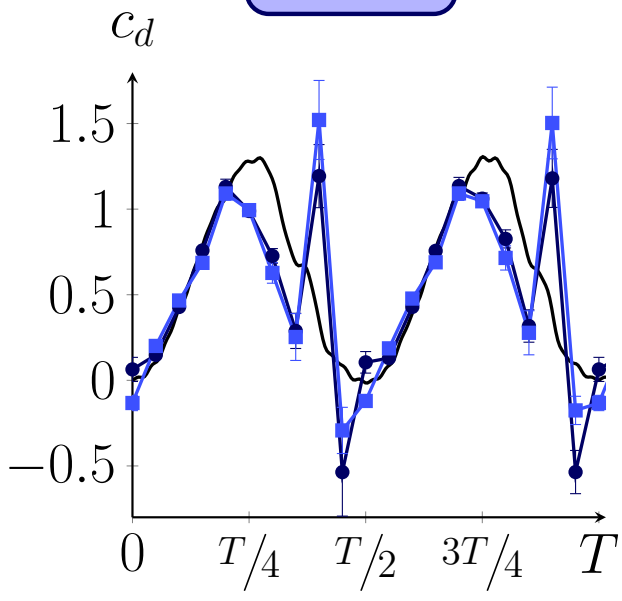
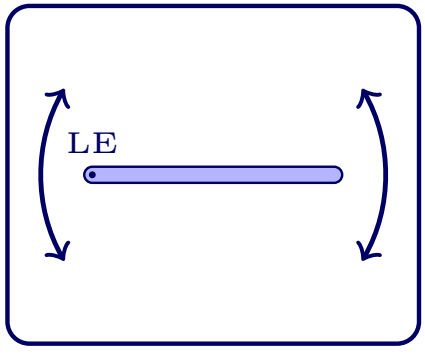


Large amplitude pitching



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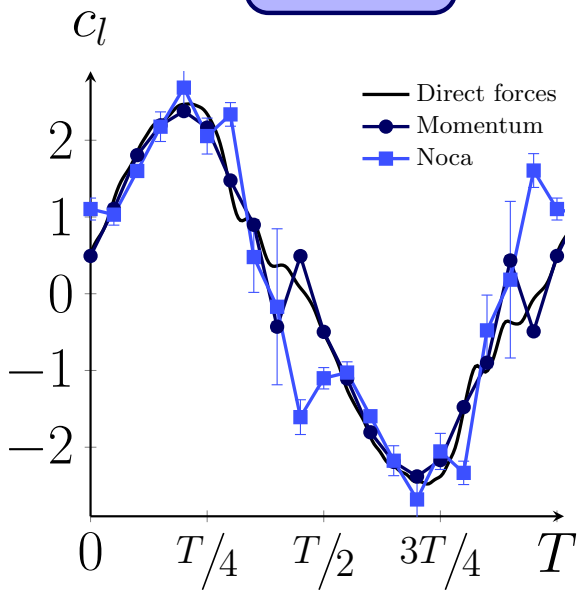

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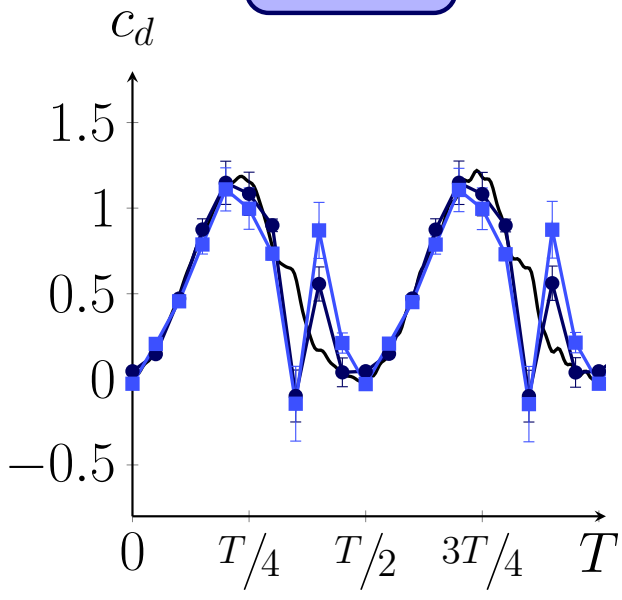
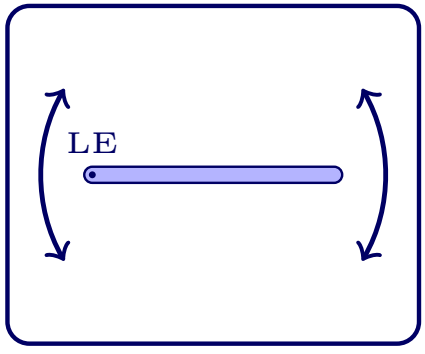


Large amplitude pitching



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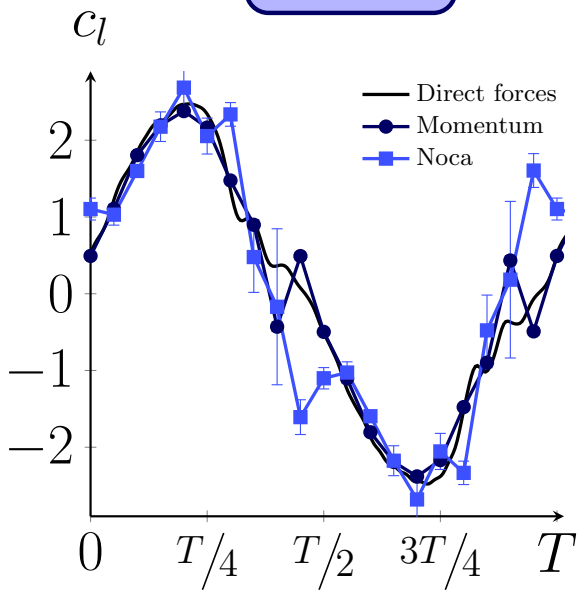

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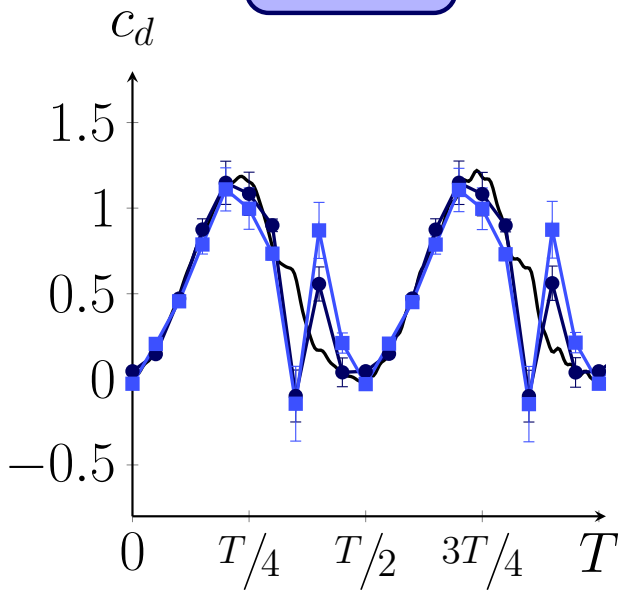
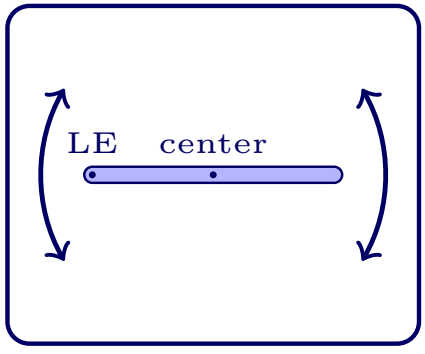
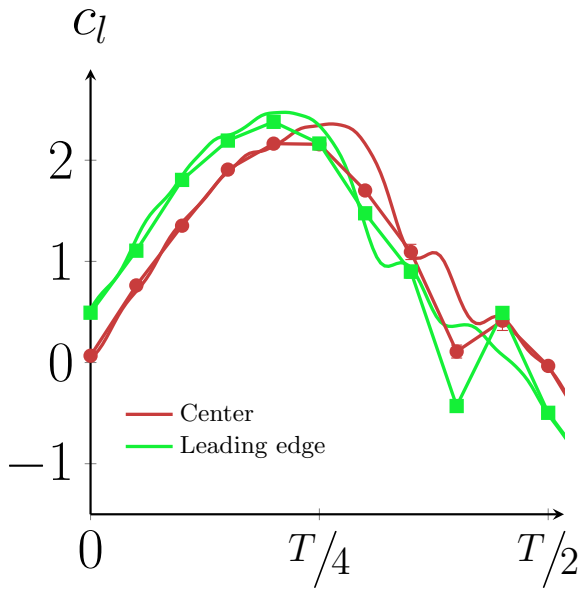


- **Mean, standard deviation and time evolution from both**
- **Noca's equation more noise sensitive**

Large amplitude pitching

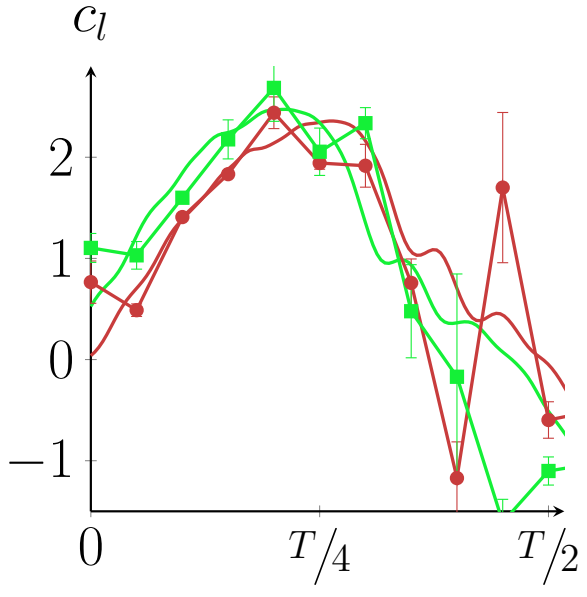




Lift

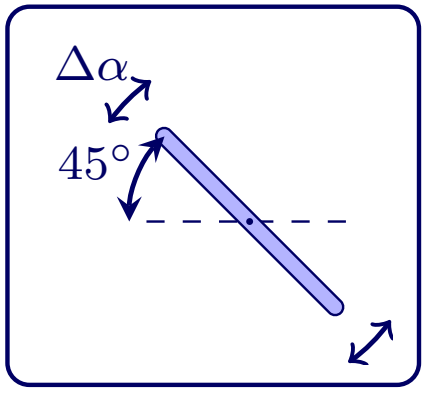
from momentum

from Noca



- **Mean, standard deviation and time evolution from both**
- **Noca's equation more noise sensitive**
- **Momentum able to compute phase-lag**

Small amplitude pitching



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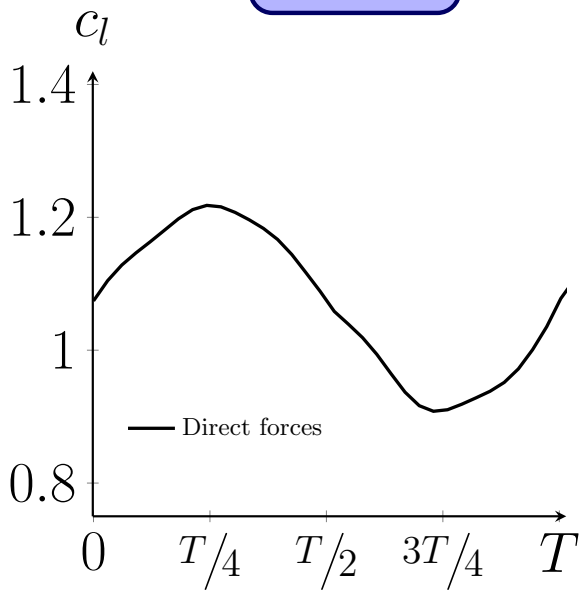

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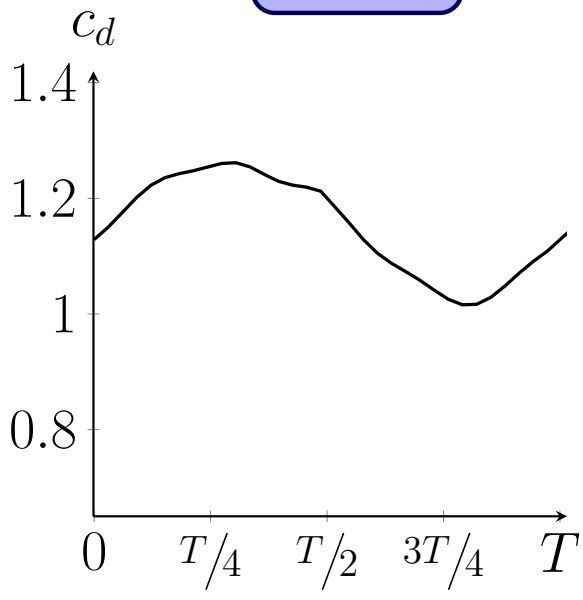
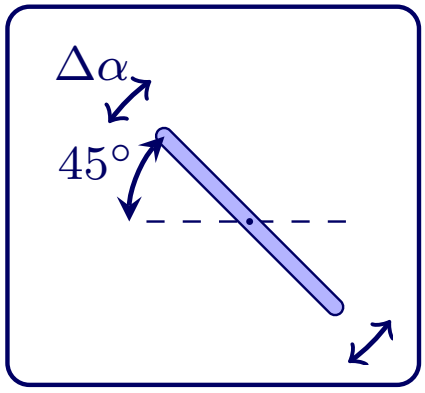


Small amplitude pitching



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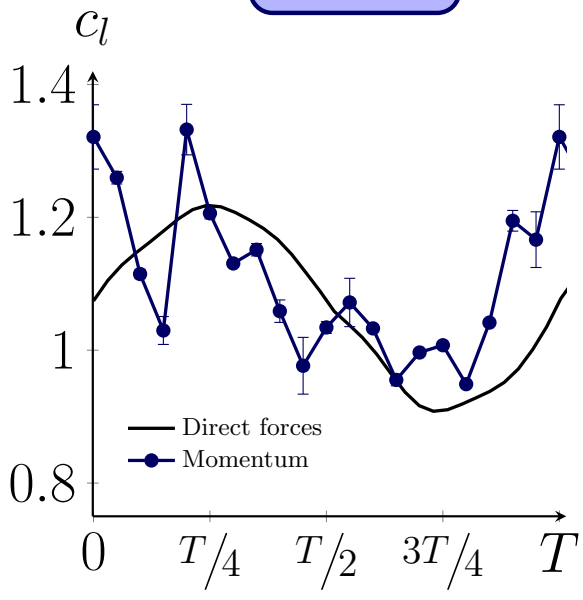

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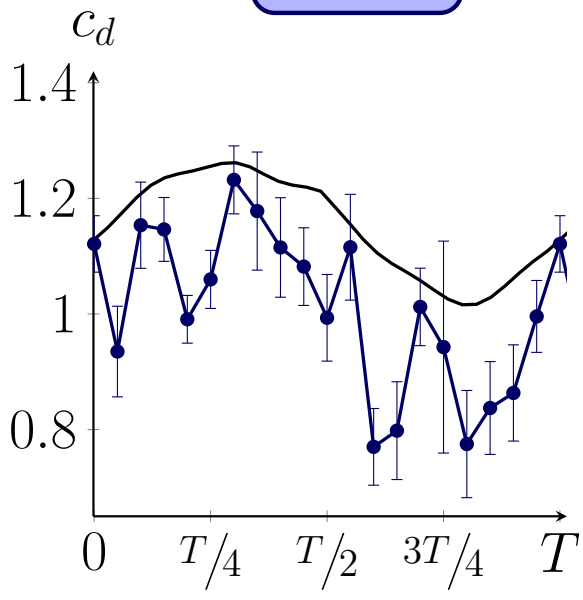
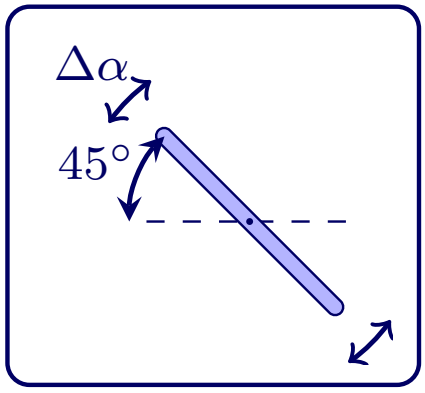


Small amplitude pitching



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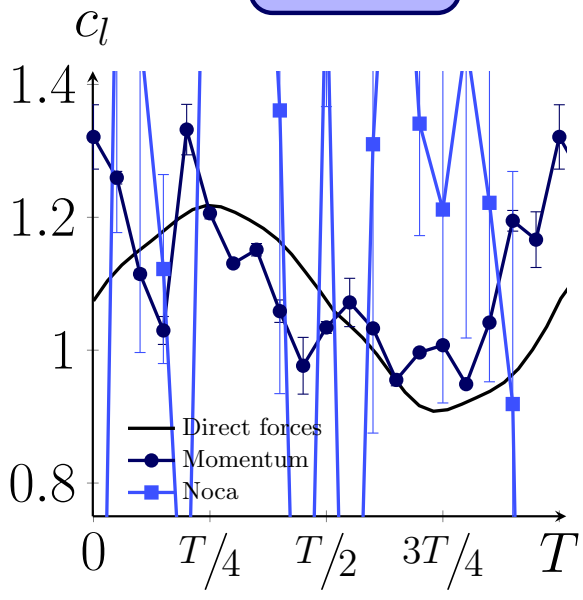

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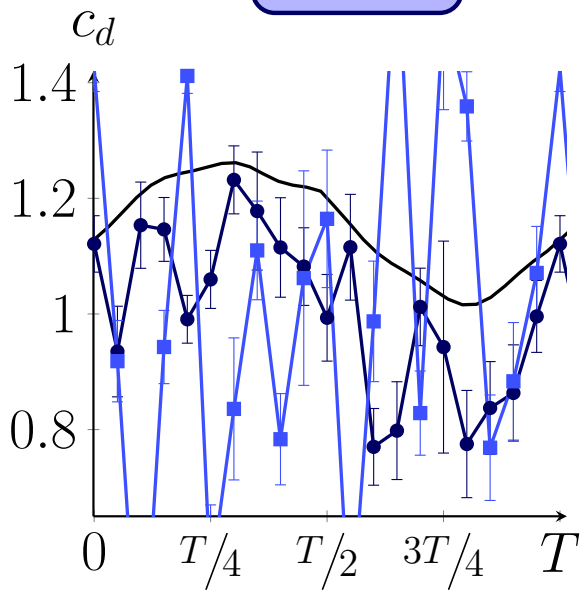
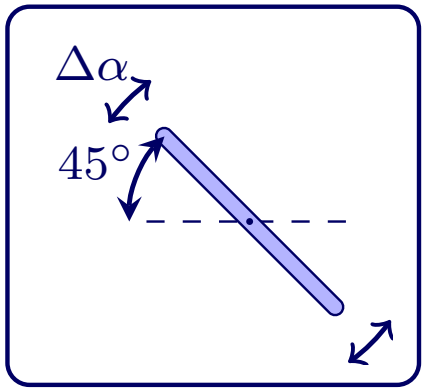


Small amplitude pitching



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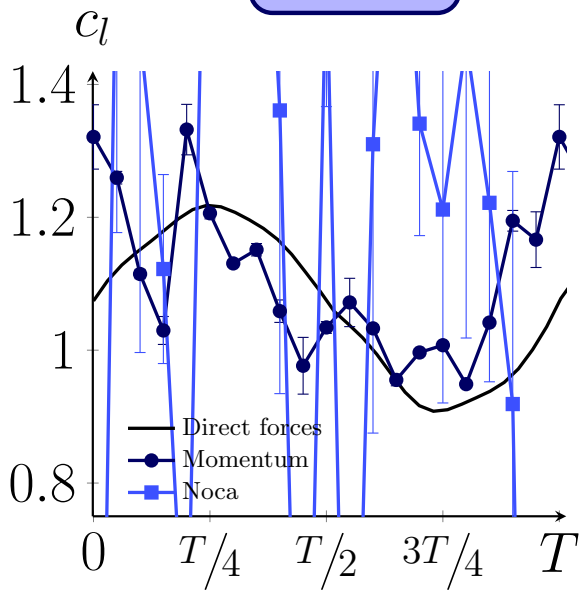

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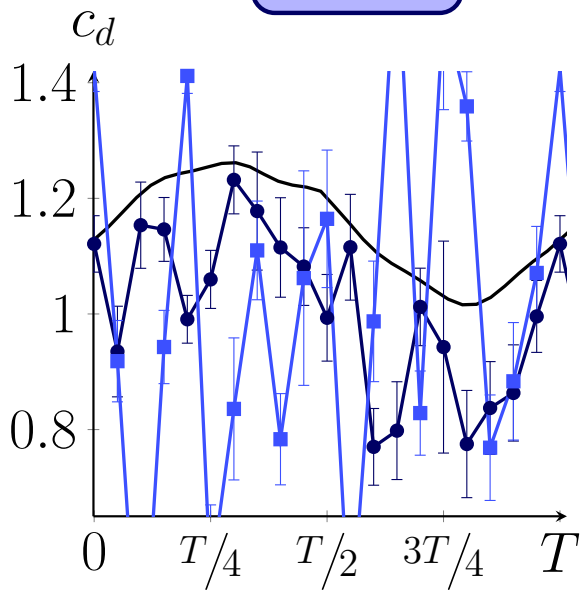
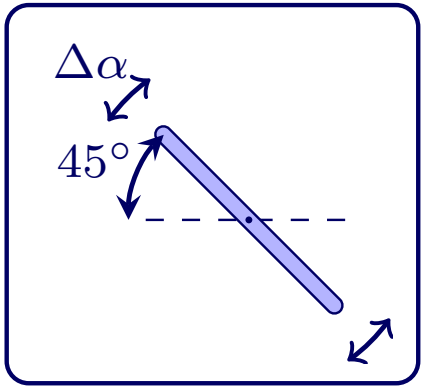
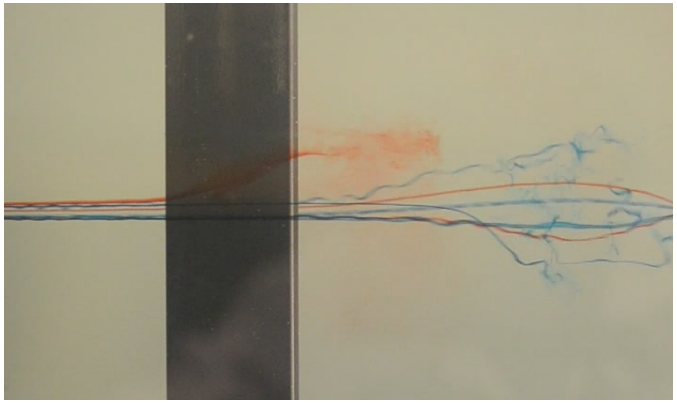


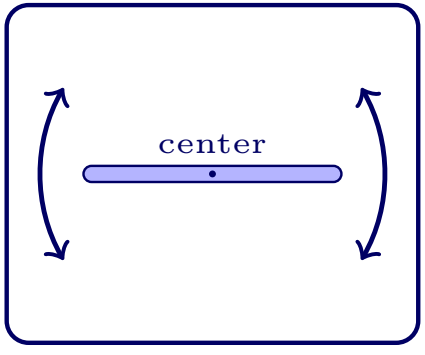
- **Only mean from momentum**
- **Unusable results from Noca's equation**

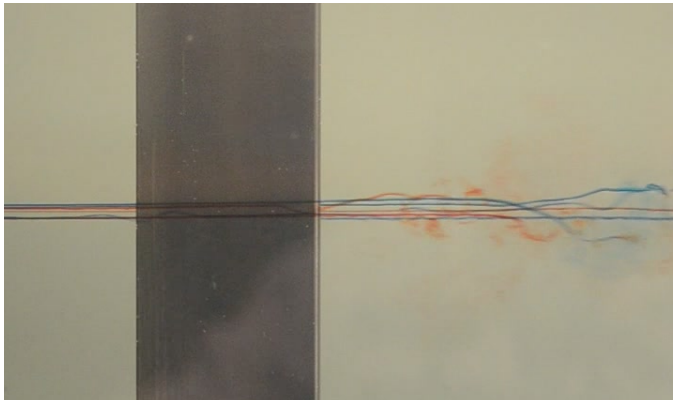
$\Rightarrow$ **Why a such big difference?**

Small amplitude pitching

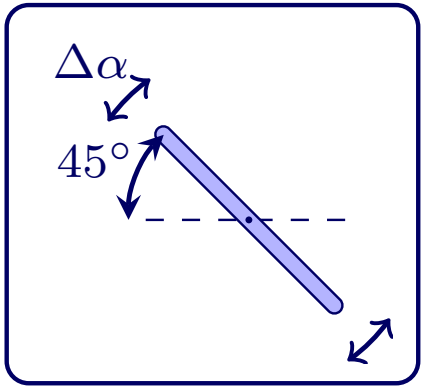


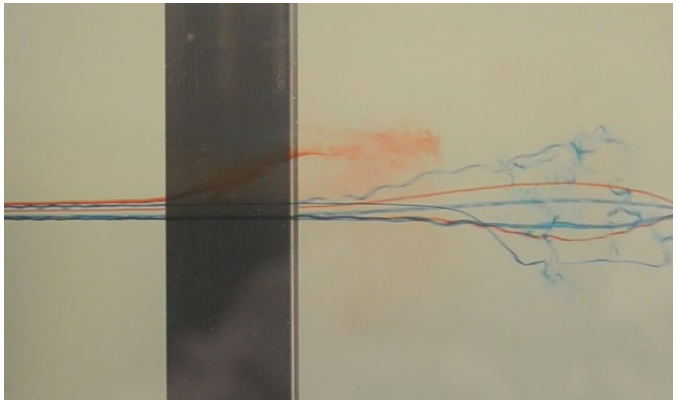


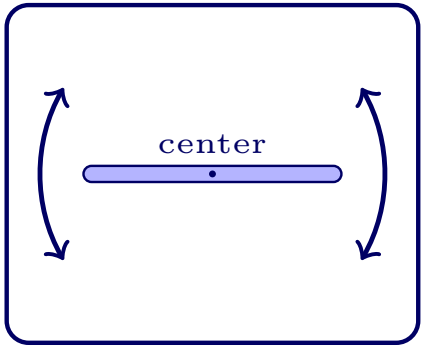


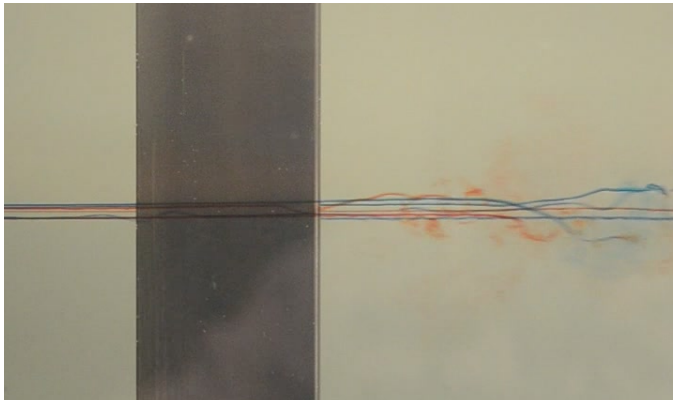


Small amplitude pitching









- **Small amplitude pitching $\Rightarrow$ flow is 3D**

$\Rightarrow$ **Impact on stitching and noise**

Conclusion and future work

Indirect methods are able to estimate forces

- Good estimation of mean coefficients
- Good estimation of temporal evolution for large amplitude
- **Methods are noise sensitive**

$\Rightarrow$ **Integral momentum equation seems to be more robust**

- Impact of 3^{rd} dimension on p
- Improvement of p correction in wake