Using 2D-PIV measurements to compute unsteady aerodynamic loads on a flat plate at high angle of attack

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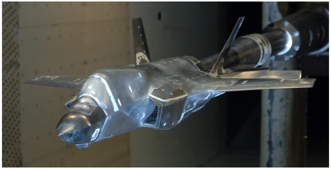
IFASD - 30 June 2015

Motivation

Forces measurement using load sensor



Not always possible

- Moving body with high inertia
- Small forces
- Sectional loads

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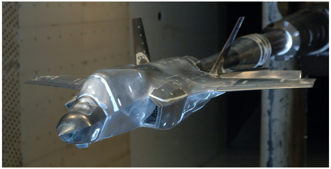

Not always possible

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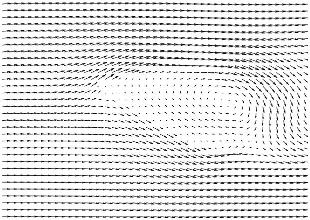
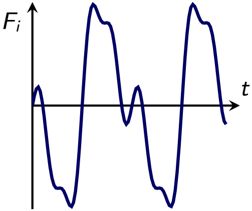
Compute forces using PIV measurements

Objective

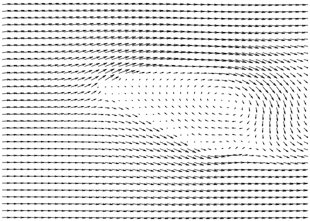
From PIV experiment $\xrightarrow{\text{calculate}}$ Indirect calculation of forces



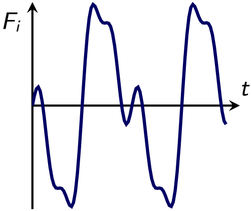


Objective

From PIV experiment



Indirect calculation of forces



Integral momentum equations

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

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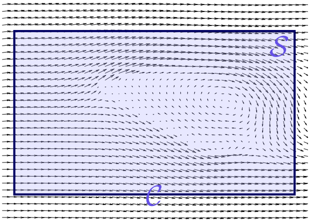

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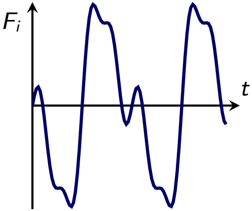

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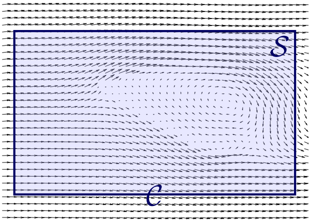

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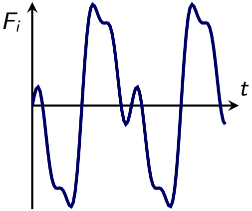

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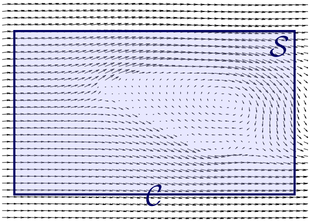

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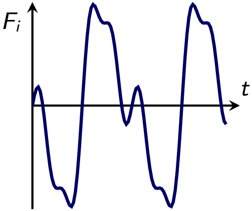

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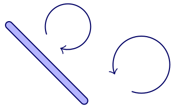
Test cases

Static flat plate



Physics of phenomenon

- Nearly periodic vortex shedding
- Phase averaging $\Rightarrow$ synchronization

$\Rightarrow$ Small amplitude pitching motion

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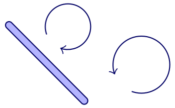

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Without synchronization

- Time averaging

$\Rightarrow$ **Mean c_l & c_d**

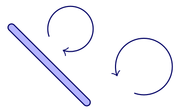
With synchronization

- Phase averaging

$\Rightarrow$ **Evolution of $c_l(t)$ & $c_d(t)$**

Test cases

Static flat plate



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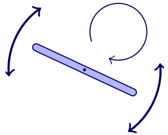
Large amplitude pitching flat plate



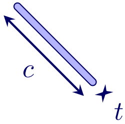
Physics of phenomenon

- Periodic shedding due to pitching
- Phase averaging using motion

$\Rightarrow$ **Evolution of $c_l(t)$ & $c_d(t)$**

Test cases

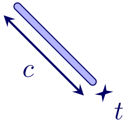
Flat plate



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

Test cases

Flat plate



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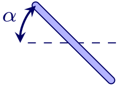
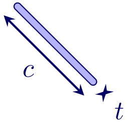
1. Static



- $\mathrm{Re} = 4 \cdot 10^4$
- $\alpha = 30^\circ$ & 45°
- Mean flow only

Test cases

Flat plate



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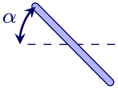

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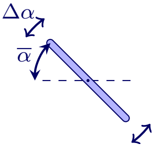
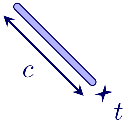
2. Small amplitude pitching



- $\alpha = \overline{\alpha}$
  $+\Delta\alpha \sin(2\pi f t)$
- $\overline{\alpha} = 30^\circ$ & 45°
- $\Delta\alpha \approx 1^\circ$
- f based
  on $\mathrm{St} = 0.155$

Test cases

Flat plate



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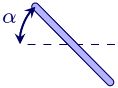

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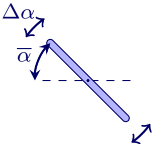

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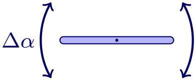
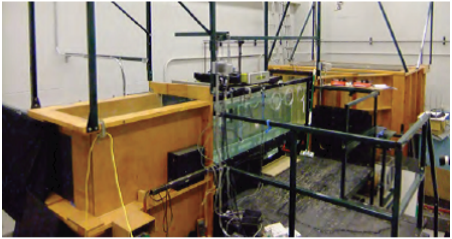


- $\mathrm{Re} = 2 \cdot 10^4$
- $\overline{\alpha} = 0^\circ$
- $\Delta\alpha = 30^\circ$
- f based on $k = 0.2$

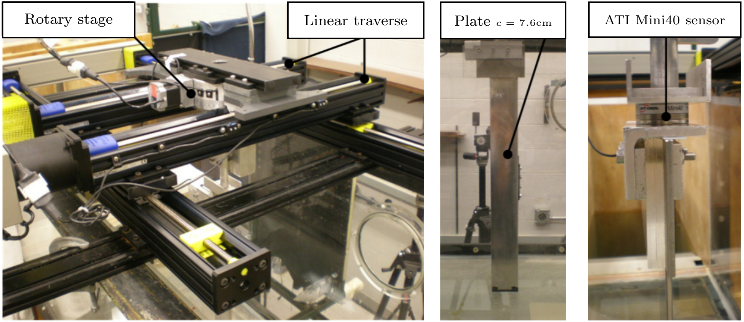
Methodology



- Water channel
- PIV
  - ⇒ Synchronization
- Direct force measurements
  - ⇒ Comparison

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

Methodology



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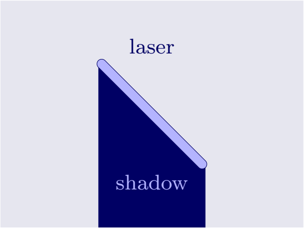

- Shadow due to mounting
- Use of symmetry
- Stitching of two images

  ⇒ Overlap use for stitching
  ⇒ Overlap may cause troubles

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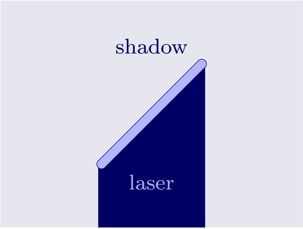
Methodology



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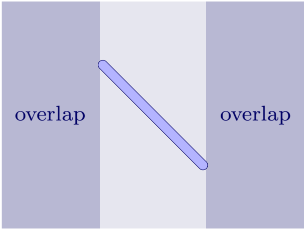

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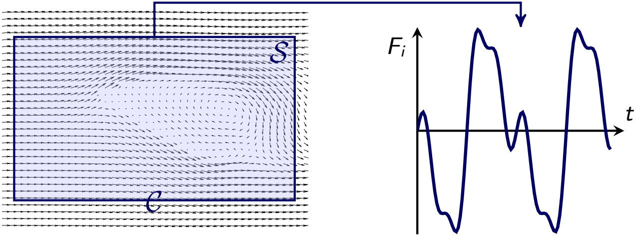
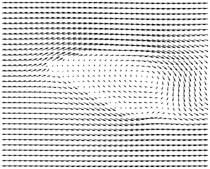


Data collection → **Pre-processing** → **Forces calculation**

Methodology: forces calculation



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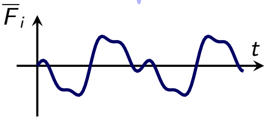

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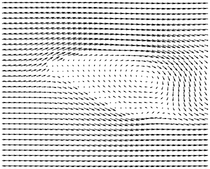

PIV data

- Phase or time averaged u_i
- Choice of $\mathcal{S}$

$$
\begin{aligned}
\overline{F}_i = &- \int_{\mathcal{S}} \rho \partial_t \overline{u}_i \, \mathrm{d}\mathcal{S} \\
&- \int_{\mathcal{C}} \rho \overline{u}_i \overline{u}_j n_j \, \mathrm{d}\mathcal{C} \\
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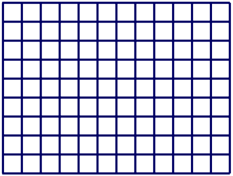

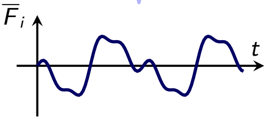

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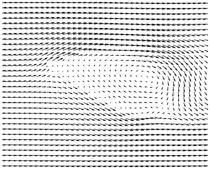

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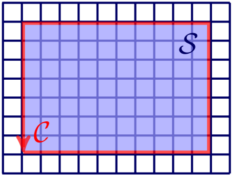

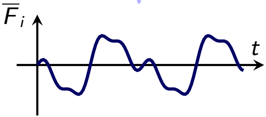

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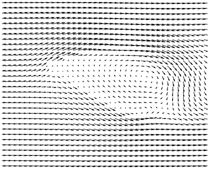

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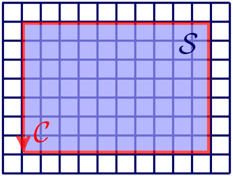
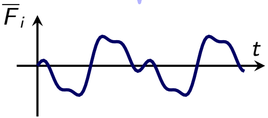
FD application

- Calculation of $\partial_t \cdot$, $\partial_{x_i} \cdot$ and $\partial_{xx_i} \cdot$

$$\begin{aligned}\overline{F}_i = & -\int_{\mathcal{S}} \rho \partial_t \overline{u}_i \,\mathrm{d}\mathcal{S} \\ & -\int_{\mathcal{C}} \rho \overline{u}_i \overline{u}_j n_j \,\mathrm{d}\mathcal{C} \\ & -\int_{\mathcal{C}} \left(\overline{p} n_i - \overline{\tau}_{ij} n_j\right) \mathrm{d}\mathcal{C} \\ & -\int_{\mathcal{C}} \rho \overline{u_i' u_j'} n_j \,\mathrm{d}\mathcal{C}\end{aligned}$$





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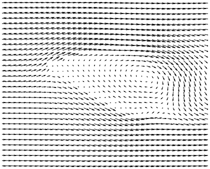

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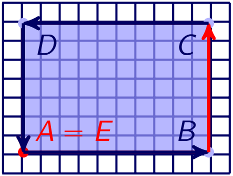


Calculation of p

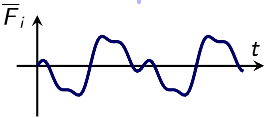
- Using NS equations

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

- Integration along $\mathcal{C}$

Correction

- Error created in wake
- $E - C$: substracted
- $B - C$: linearly spread



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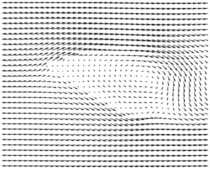

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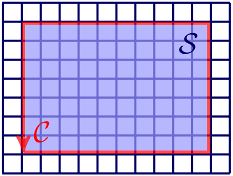
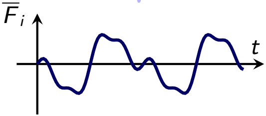
- $E - C$: substracted
- $B - C$: linearly spread

$$\overline{F}_i = -\int_{\mathcal{S}} \rho \partial_t \overline{u}_i \, \mathrm{d}\mathcal{S} - \int_{\mathcal{C}} \rho \overline{u}_i \overline{u}_j n_j \, \mathrm{d}\mathcal{C} - \int_{\mathcal{C}} \left(\overline{p} n_i - \overline{\tau}_{ij} n_j \right) \mathrm{d}\mathcal{C} - \int_{\mathcal{C}} \rho \overline{u'_i u'_j} n_j \, \mathrm{d}\mathcal{C}$$



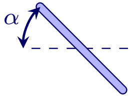
$\overline{F}_i$ calculation

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



Static

α	$\alpha = 30^\circ$		$\alpha = 45^\circ$	
	$\overline{c_l}$	$\overline{c_d}$	$\overline{c_l}$	$\overline{c_d}$
Indirect calculation	1.05 ± 0.01	0.60 ± 0.03	1.07 ± 0.08	1.08 ± 0.03
Direct measurement	0.97 ± 0.04	0.62 ± 0.03	1.02 ± 0.09	1.11 ± 0.12



Static

	$\alpha = 30^\circ$		$\alpha = 45^\circ$	
α	$\overline{c_l}$	$\overline{c_d}$	$\overline{c_l}$	$\overline{c_d}$
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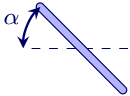

Static

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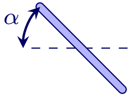

Meaning of standard deviation

- Indirect calculation
  $\Rightarrow$ 7 different surfaces $\mathcal{S}$
- Direct measurement
  $\Rightarrow$ averaging measurements

Static

α	$\alpha = 30^\circ$		$\alpha = 45^\circ$	
	$\overline{c_l}$	$\overline{c_d}$	$\overline{c_l}$	$\overline{c_d}$
Indirect calculation	1.05 ± 0.01	0.60 ± 0.03	1.07 ± 0.08	1.08 ± 0.03
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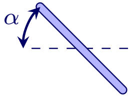

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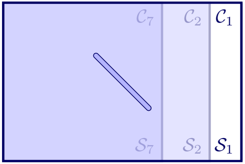

Static

α	$\alpha = 30^\circ$ $\overline{c_l}$	$\alpha = 30^\circ$ $\overline{c_d}$	$\alpha = 45^\circ$ $\overline{c_l}$	$\alpha = 45^\circ$ $\overline{c_d}$
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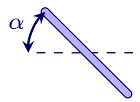

Meaning of standard deviation

- Indirect calculation
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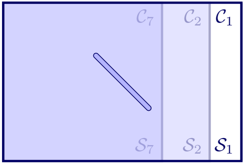
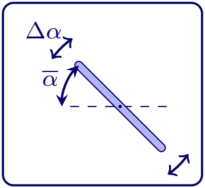
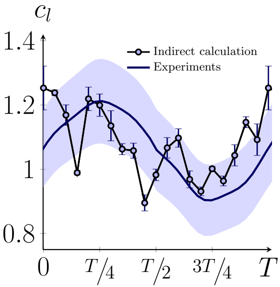
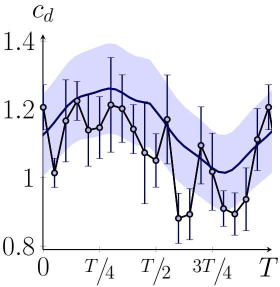
  $\Rightarrow$ averaging measurements



Small amplitude pitching

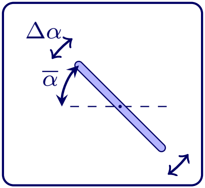


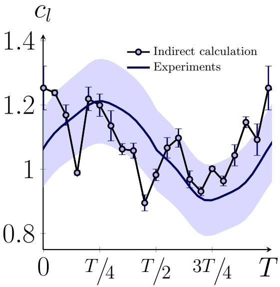


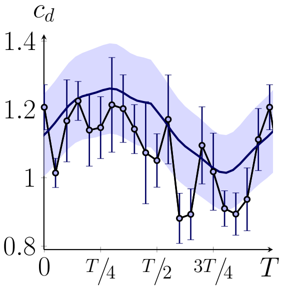


	$\alpha = 30^\circ$				$\alpha = 45^\circ$			
α	$\overline{c_l}$	c_l^{rms}	$\overline{c_d}$	c_d^{rms}	$\overline{c_l}$	c_l^{rms}	$\overline{c_d}$	c_d^{rms}
Indirect calculation	1.14	0.15	0.61	0.14	1.08	0.10	1.07	0.12
Direct measurement	1.08	0.06	0.69	0.02	1.06	0.11	1.15	0.09

Small amplitude pitching







	$\alpha = 30^\circ$				$\alpha = 45^\circ$			
α	$\overline{c_l}$	c_l^{rms}	$\overline{c_d}$	c_d^{rms}	$\overline{c_l}$	c_l^{rms}	$\overline{c_d}$	c_d^{rms}
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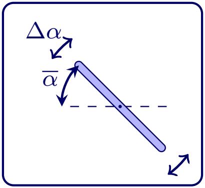
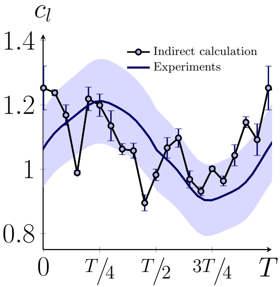
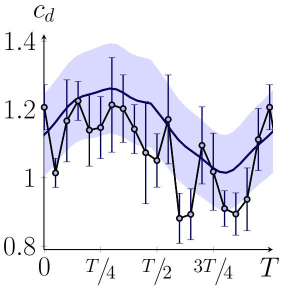
Small amplitude pitching







	$\alpha = 30^\circ$				$\alpha = 45^\circ$			
α	$\overline{c_l}$	c_l^{rms}	$\overline{c_d}$	c_d^{rms}	$\overline{c_l}$	c_l^{rms}	$\overline{c_d}$	c_d^{rms}
Indirect calculation	1.14	0.15	0.61	0.14	1.08	0.10	1.07	0.12
Direct measurement	1.08	0.06	0.69	0.02	1.06	0.11	1.15	0.09

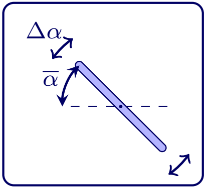
Methodology

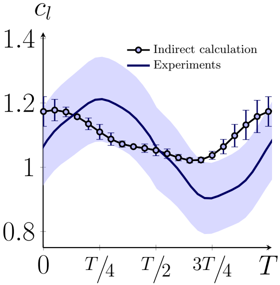
DMD finds single frequency modes ϕ_i^{DMD}

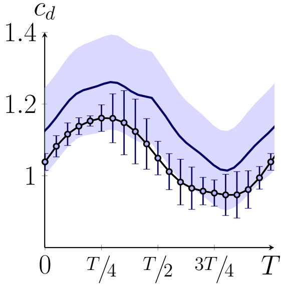
$$\mathbf{u}\left(x,y,t\right) = \sum_{i=1}^{N} \underbrace{a_i^{\text{DMD}}}_{\text{amplitude}} \; \underbrace{\exp\left(\lambda_i^{\text{DMD}} t\right)}_{\substack{\text{time}\\ \text{evolution}}} \; \underbrace{\phi_i^{\text{DMD}}\left(x,y\right)}_{\substack{\text{spatial}\\ \text{mode}}}$$

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

Small amplitude pitching with DMD

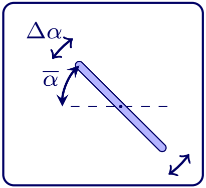


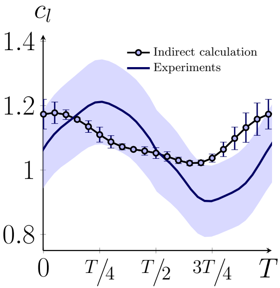


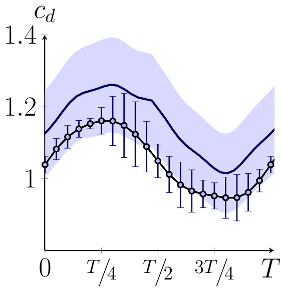


	30°				45°			
α	$\overline{c_l}$	c_l^{rms}	$\overline{c_d}$	c_d^{rms}	$\overline{c_l}$	c_l^{rms}	$\overline{c_d}$	c_d^{rms}
Indirect (without DMD)	1.14	0.15	0.61	0.14	1.08	0.10	1.07	0.12
Indirect (with DMD)	1.14	0.09	0.61	0.03	1.10	0.06	1.05	0.08
Direct measurement	1.08	0.06	0.69	0.02	1.06	0.11	1.15	0.09

Small amplitude pitching with DMD







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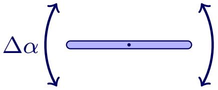
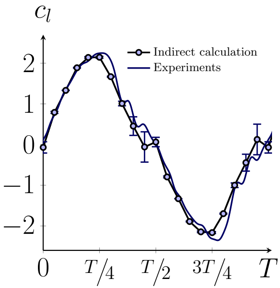
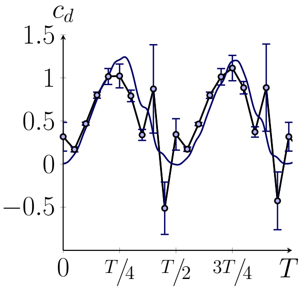
Large amplitude pitching

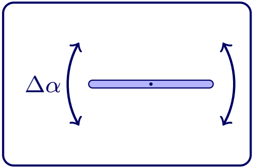


	$0^\circ \pm 30^\circ$			
α	$\overline{c_l}$	c_l^{rms}	$\overline{c_d}$	c_d^{rms}
Indirect calculation	0.02	1.48	0.58	0.44
Direct measurement	0.03	1.45	0.55	0.42





Large amplitude pitching



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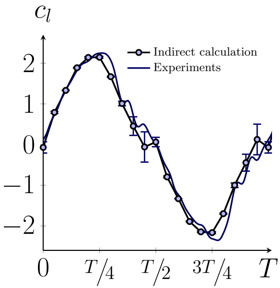
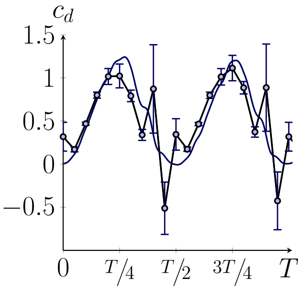
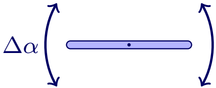




Large amplitude pitching



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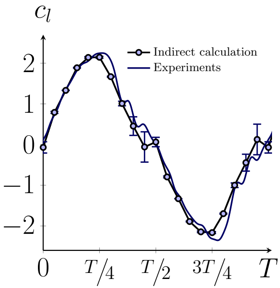

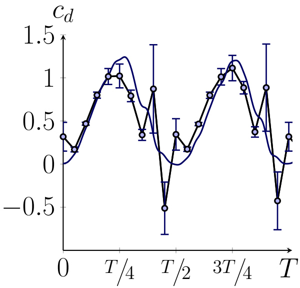

Conclusion and future work

Indirect method is able to estimate forces

- Good estimation of mean coefficients
- Good estimation of temporal evolution for large amplitude
- **Method is noise sensitive**

$\Rightarrow$ **DMD can be used to reduce the noise**

- Further study impact of resolutions, window size, ...
- Comparison with other formulations