High-fidelity simulations of the unsteady response of an NLF airfoil

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Background

and motivation

- Large push in the aerospace industry to fly greener.
  - Laminar airfoils is proposed as the low-hanging fruit for achieving high skin friction reduction.

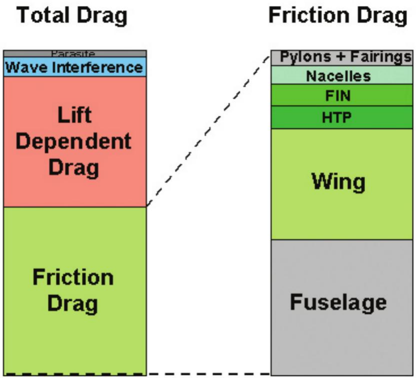
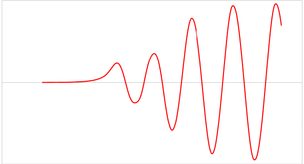


Figure 1. Typical drag breakdown of a transport aircraft.

Aeroelasticity

"A systematic aeroelastic investigation for laminar wings is unknown in the literature." Mai et al. (2011) IFASD.

Aeroelastic instability



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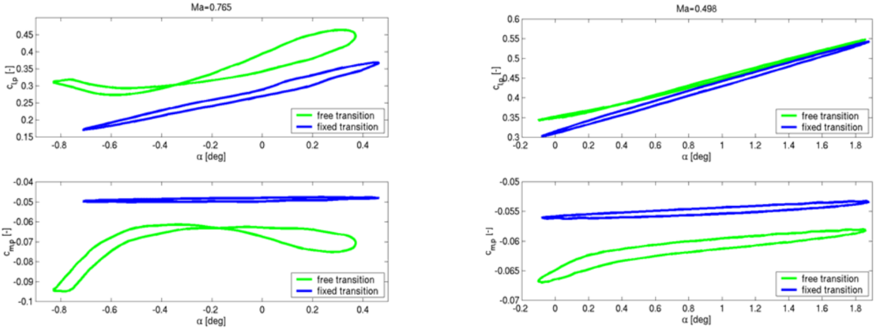
- Non-linear aerodynamic response of an laminar airfoil to harmonic pitch motion.
    - Both transonic and subsonic flows.



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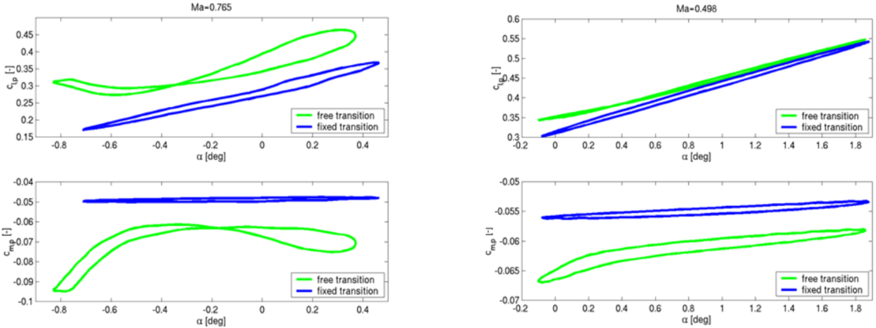
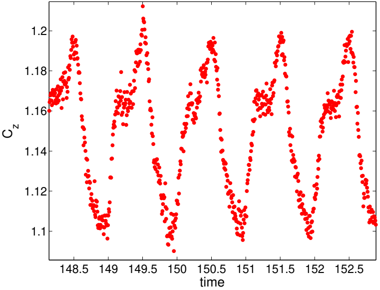
- Non-linear aerodynamic response of an laminar airfoil to harmonic pitch motion.
  - Both transonic and subsonic flows.
- Non-linearities substantially reduced when the transition is fixed.



Aeroelasticity

Subsonic results

- Similar results obtained in unsteady experiments on laminar airfoil at KTH (subsonic conditions).

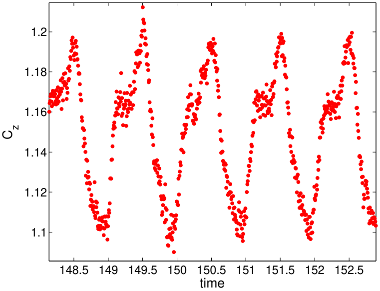


Lokatt (2017)

Aeroelasticity

Subsonic results

- Similar results obtained in unsteady experiments on laminar airfoil at KTH (subsonic conditions).
- Classical unsteady theories rely on linear assumptions.
  - Glauert (1930), Theodorsen (1935), von Kármán & Sears (1938)
- What are the flow dynamics behind the non-linear response?



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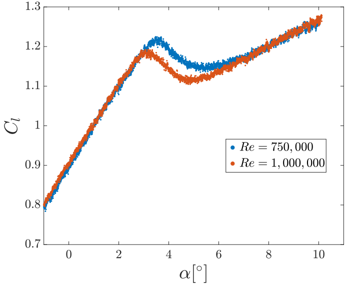
Parameter identification

Static characteristics

- What mean angle of attack to study? Non-linear behavior observed only for certain angles of attack.
  - Experimental results.



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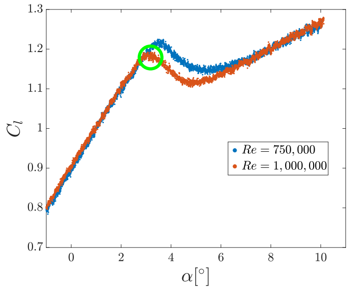

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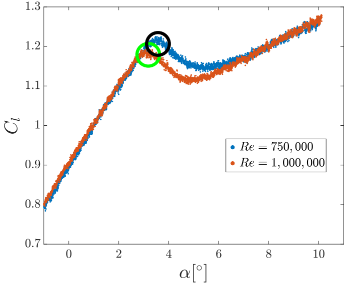

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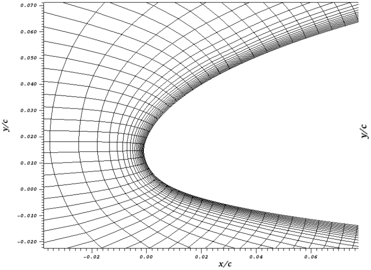
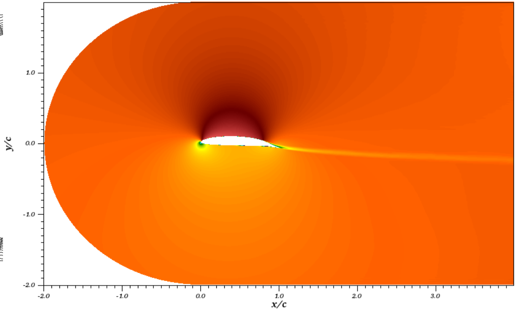
Numerical simulation

Computational Setup

Large Eddy Simulation

- Nek5000. High-order Spectral-Element method.
  - 9^{th} order polynomial representation.
  - ALE for mesh motion.





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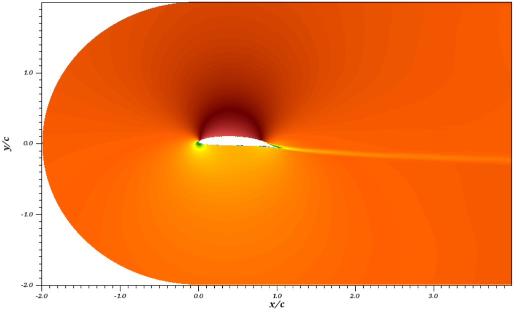

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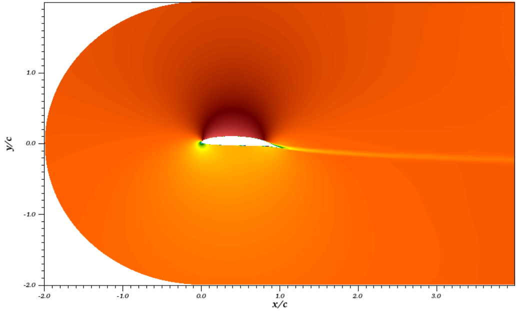
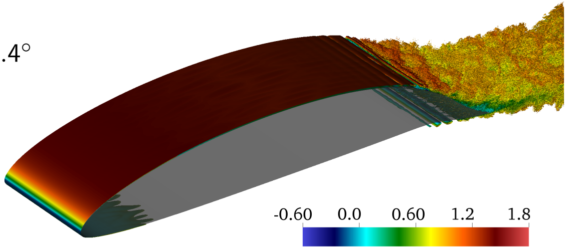
- Wall-resolved LES. ($\Delta y^{+} < 1$)
- 1.4 Billion grid points.



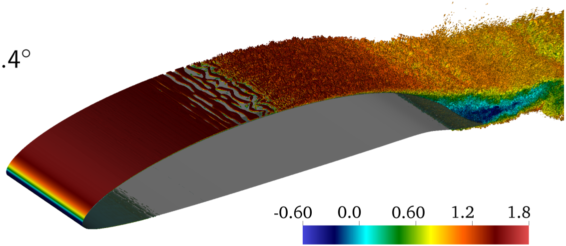
Stationary Simulations

Static characteristics

$\alpha = 2.4^\circ$



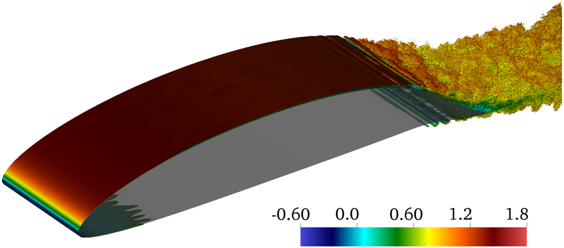
$\alpha = 4.4^\circ$



Pitching airfoil

Unsteady response

$$\alpha(t) = \alpha_0 + \Delta\alpha \sin(\Omega t)$$



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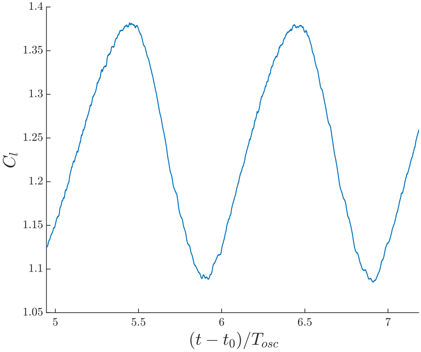

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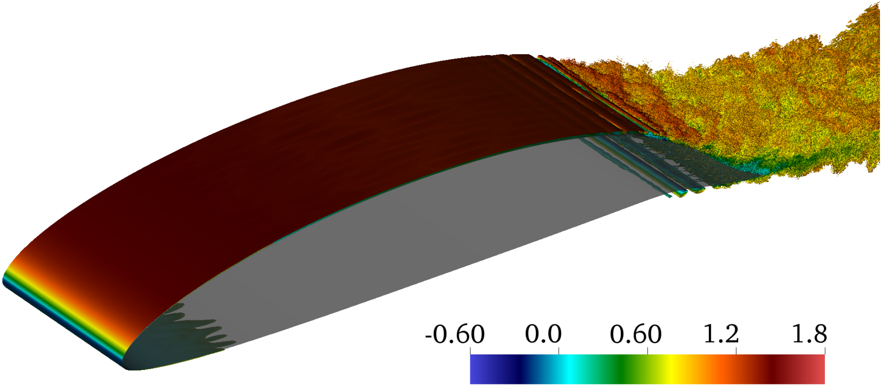
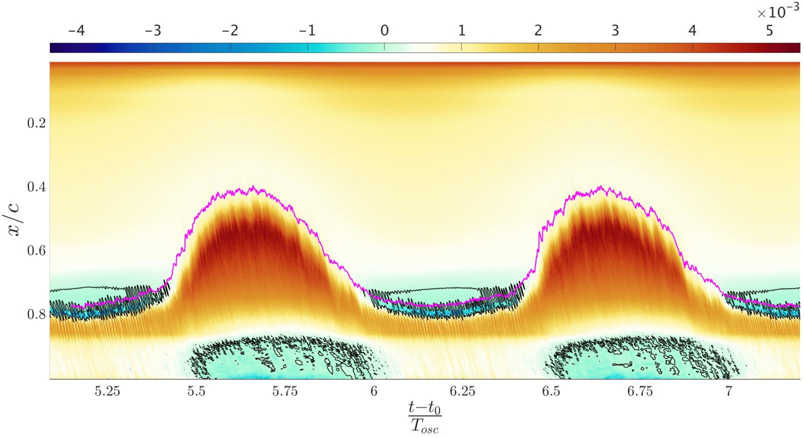


Pitching airfoil

Boundary-layer transition



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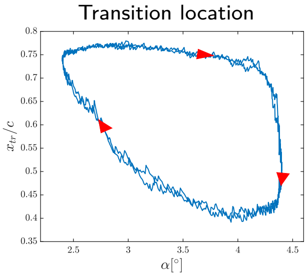

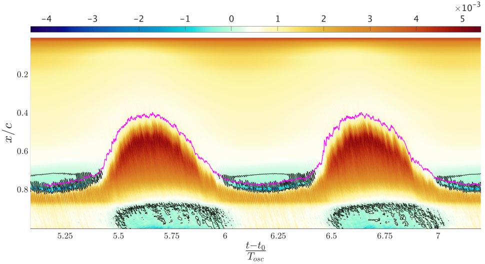

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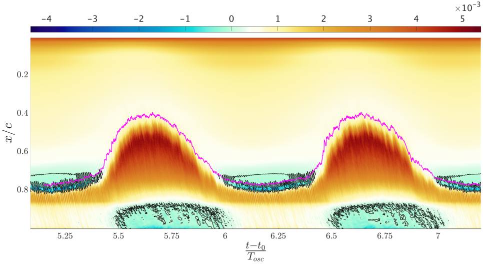
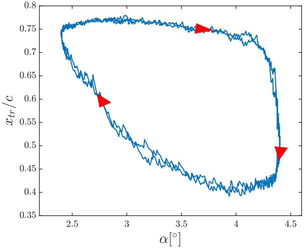
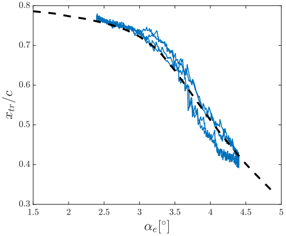


Transition location



⇕ Phase-lag



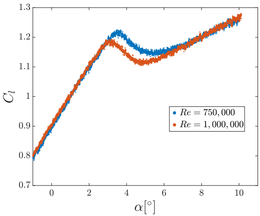
Pitching airfoil

Simple empirical model

- Boundary-layer has a quasi-steady evolution.

$$\text{Phase lag model: } C_L(t) = \underbrace{A_1 cos(\omega t + \theta)}_{\text{added mass}} + \underbrace{C_L^{static}(\alpha_e)}_{\text{quasi-steady lift}}$$

$$\text{Effective angle: } \alpha_e = \alpha_0 + \Delta\alpha \sin(\Omega t + \phi)$$



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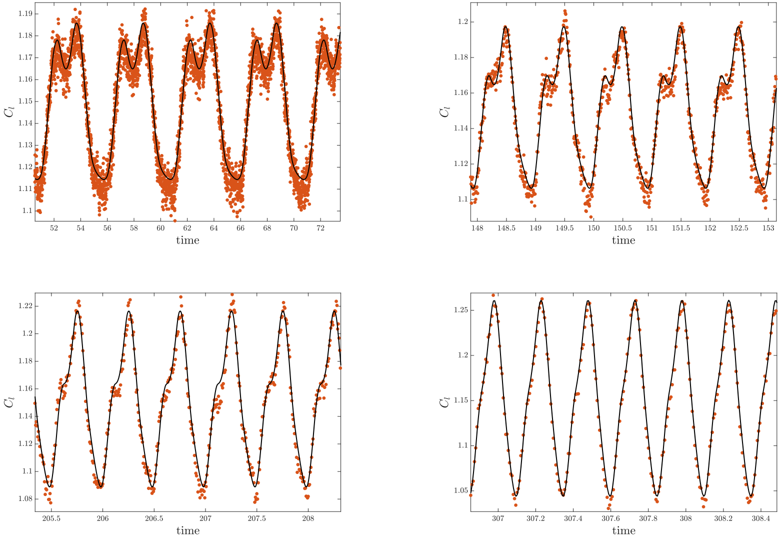

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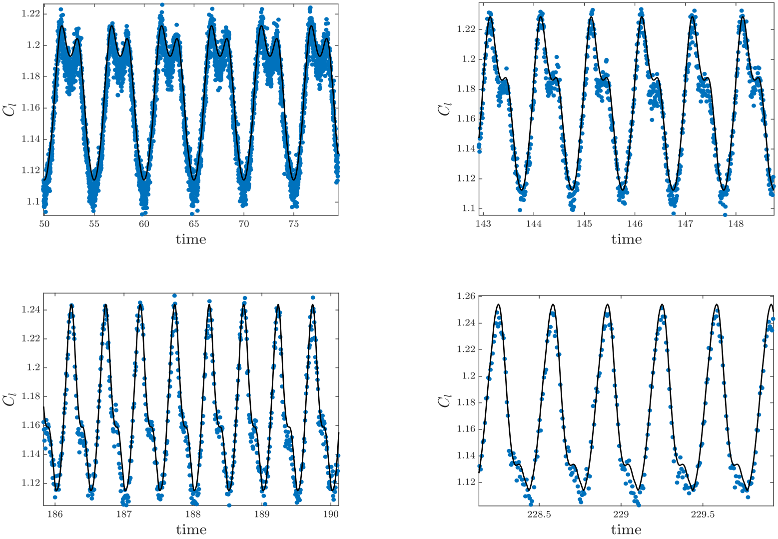

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Identify non-linearity characteristics.

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  - Identifies the exact source and structure of the non-linearities.
  - Directly linked to the static data of the airfoil.
  - Non-linear part of the response is reduced to knowing one parameter (phase-lag).

Linear Analysis

Linear forced-response

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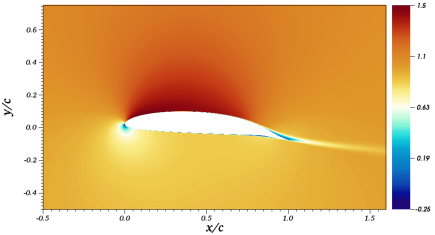

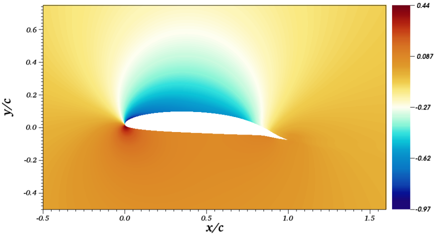

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- Think of the boundary conditions as forcing at the boundary:
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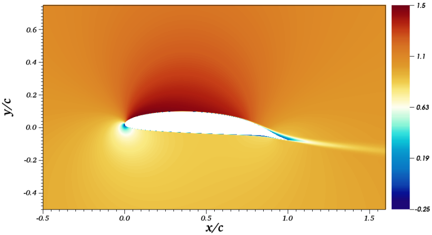
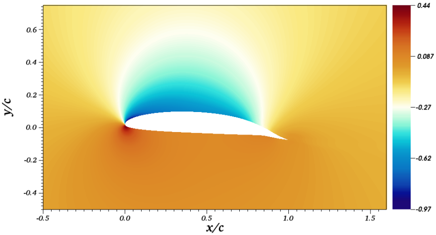
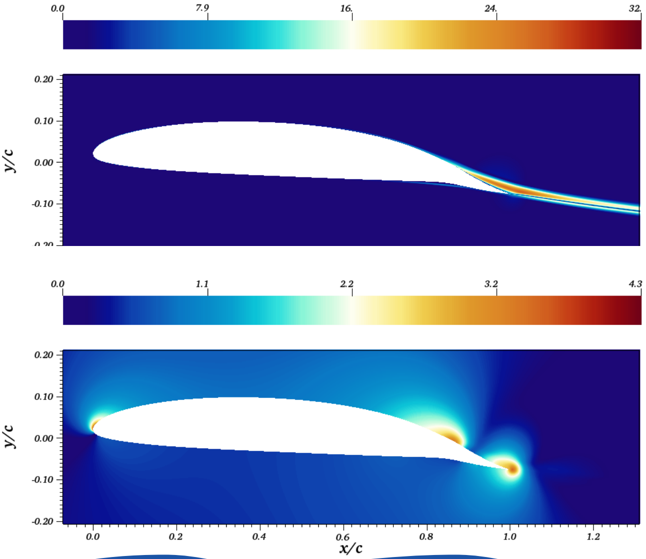
- Linear simulations with the mean angle of attack $\alpha_0 = 3.4^\circ$ as the base flow.
  - 2D response for several different frequencies.





Linear Analysis

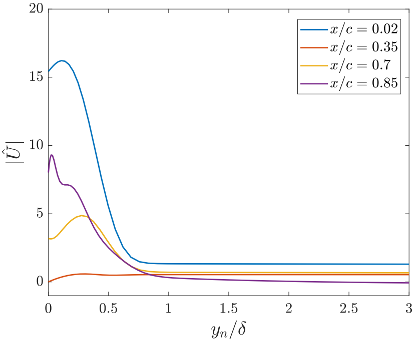
Response amplitude for $k = 0.4$

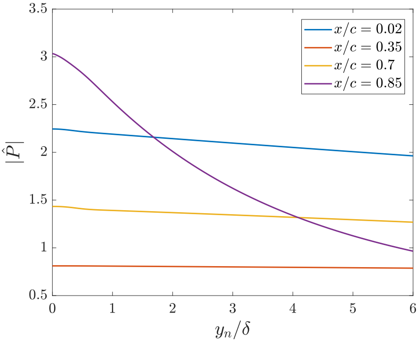


Linear Analysis

Response profiles

- Wall-normal profiles of the response.





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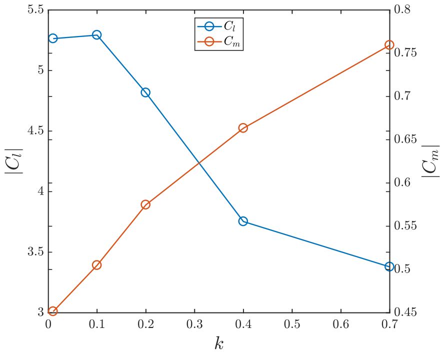
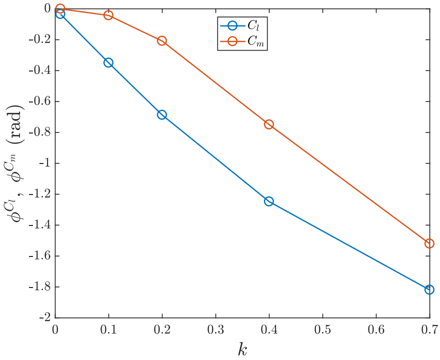
Response profiles

- Amplitude and phase of linear forces.

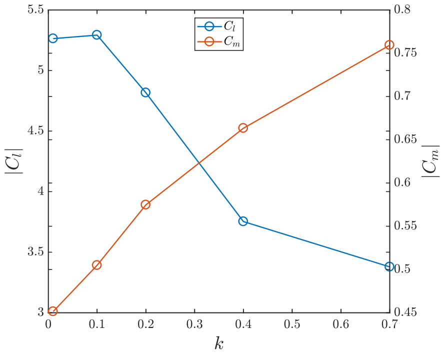


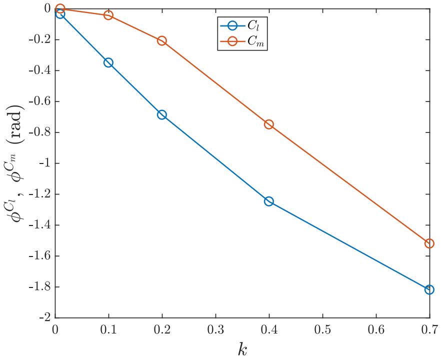


Linear Analysis

Response profiles

- Amplitude and phase of linear forces.
  - Both C_l and C_m are always lagging.
  - Lag is almost linear with k





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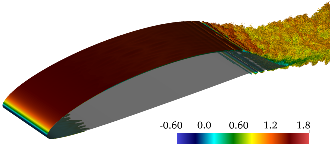
- Wall-resolved LES for a pitching laminar flow airfoil at $Re_c = 750,000$
  - Unsteady transition can be related to the static characteristics with a simple phase-lag.



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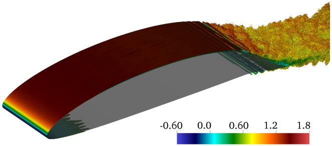

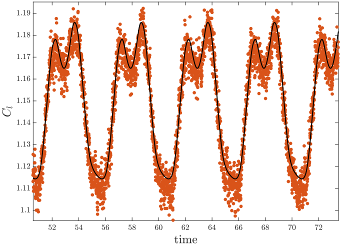

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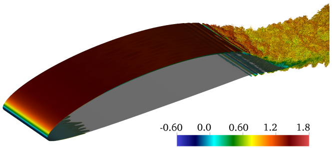
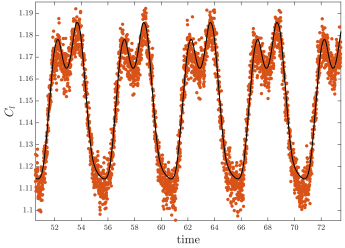
- 2D Linear analysis of a pitching airfoil
  - Very high response inside the boundary layer with 3 distinct regions of high pressure.





Acknowledgments

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- The computations were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at the PDC Center for High Performance Computing at the Royal Institute of Technology (KTH). Simulations were also carried out at the High Performance Computing Center, Stuttgart (HLRS), with the computer time provided by the 15th PRACE Project Access Call (number 2016163965).
- We would like to thank Dr. Eller and Dr. Lokatt for sharing the experimental data.

Thank you for your attention.

Any questions?