Lectures on PIV

Last developments and applications

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PIV-base pressure and force measurement

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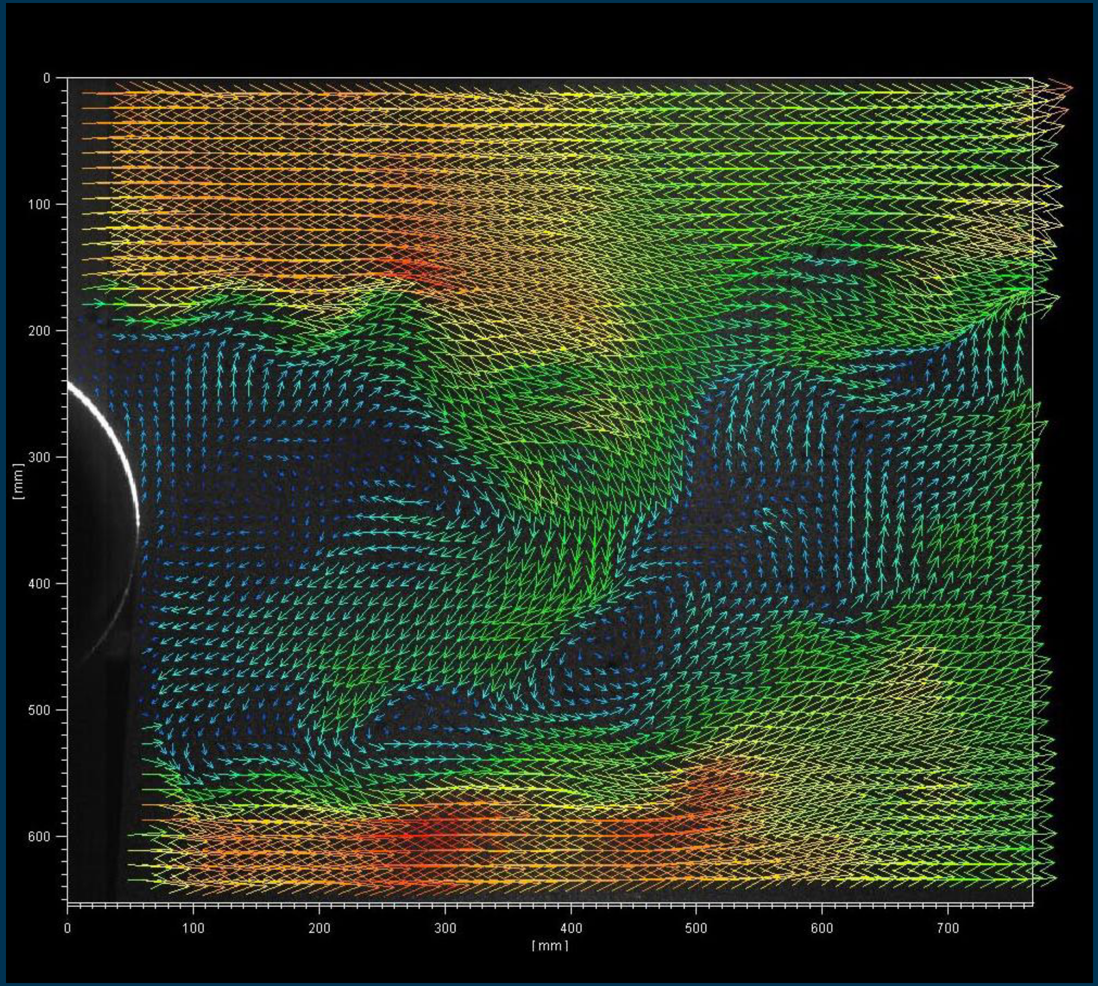
Outline



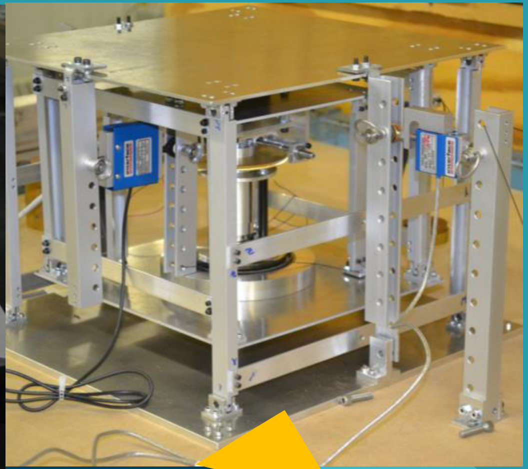
- Pressure extraction from planar velocimetry data
  - Models
  - Boundary contitions
  - Models comparison
  - Dealing with limited resources
- Force extraction from planar velocimetry data
  - Models
  - An example
- Uncertainty sources

PIV-based measurements: why

- Flow field information and mechanical loads are traditionally obtained by separate techniques:
  - Pressure tappings for surface pressure distribution
  - Force balances for integral loads
  - Probes for point-wise measurements

PIV-based measurements:

- Appealing approach to establish a direct link between flow behaviour and loads
- Measuring pressure where direct measurement is impossible



Pressure extraction: principles

Two main approaches have been proposed over the years:

- Integration of the Navier-Stokes momentum equation (Gurka et al. 1999)

$$\boldsymbol{\nabla} p = -\rho\left(\frac{\partial \boldsymbol{u}}{\boldsymbol{\partial} t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u}\right) + \mu\nabla^2\boldsymbol{u}$$

- Solution of the Poisson equation fro the pressure (Baur & Kongeter 1999)

$$-\nabla^2 p = -\rho\boldsymbol{\nabla}\cdot((\boldsymbol{u}\cdot\boldsymbol{\nabla})u)$$

Hypothesis

- *2D*
- *Incompressible*

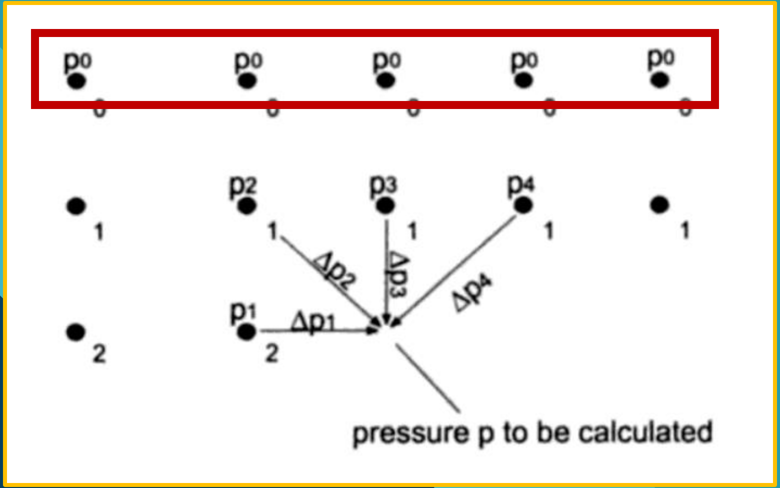
$$(\boldsymbol{\nabla}\cdot\boldsymbol{u} = \boldsymbol{0})$$

Pressure extraction: NS momentum

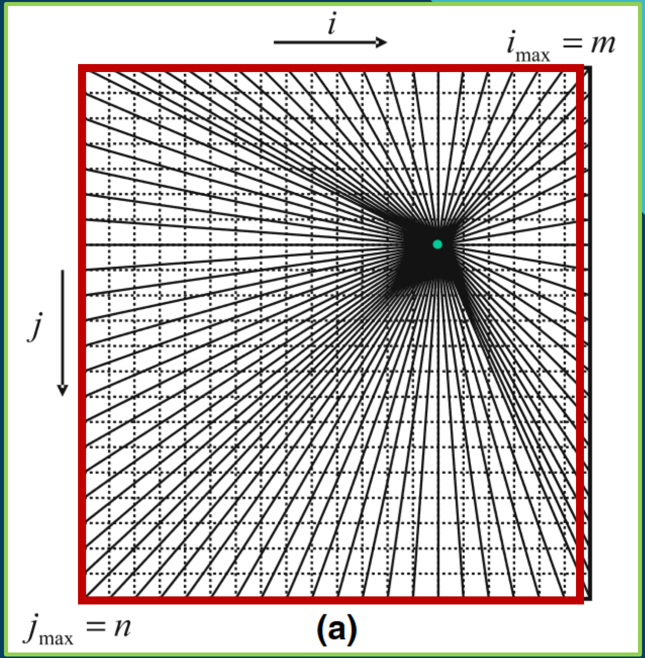
Integration of the NS momentum equation by means of spatial marching scheme

- Systematic marching
- Field erosion

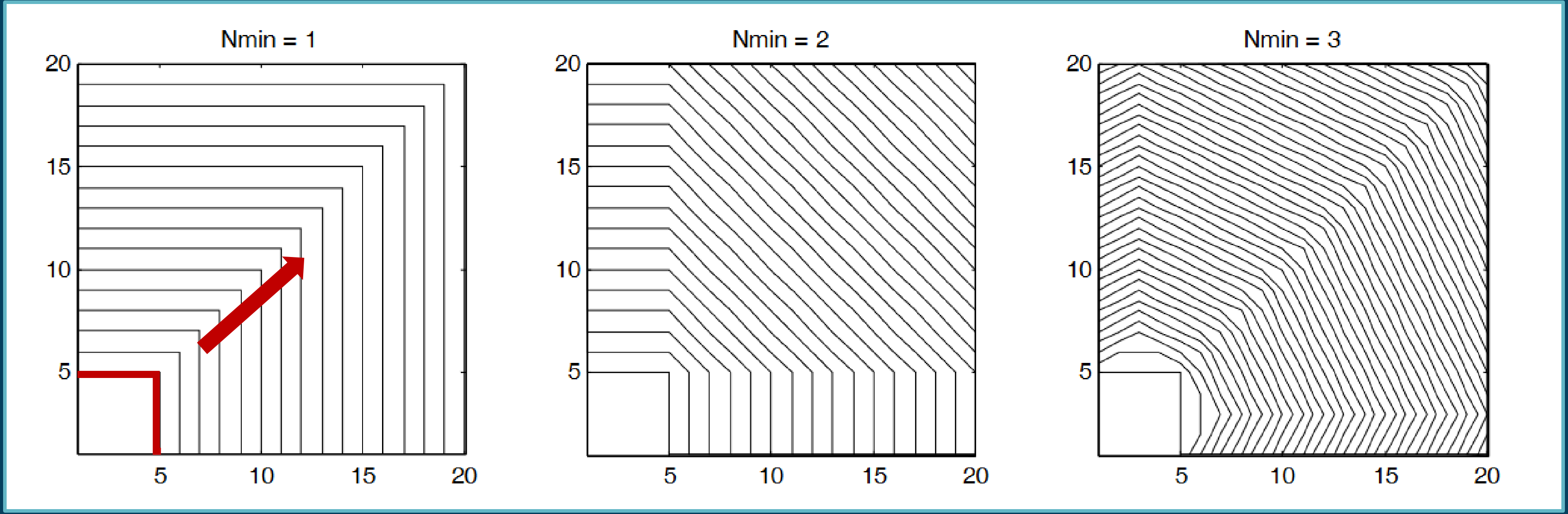
Baur & Kongeter 2007



Liu & Katz 2006



Oudheusden & Souverein 2007



Pressure extraction: Poisson

$$-\nabla^2 p = -\rho \nabla \cdot ((\boldsymbol{u} \cdot \nabla)\boldsymbol{u})$$

Solution of the Poisson equation for the pressure

- By iterative method
- Despite the incompressibility constraint, the pressure field can still be time-dependent

- Neumann Boundary conditions

- Dirichlet Boundary conditions

Pressure extraction: Boundary Conditions treatment

- Poisson requires BC on the entire contour of the integration domain
- NS requires BC on a limited region (even a single point!)

Poisson more stable with Dirichlet conditions only!

[Auteri, 2015]

- Neumann BC from momentum equation (Gurka et al. 1999)
- Dirichlet BC from pressure measurements
  - Bernoulli equation (Hp: irrotational regions)
  - Pressure tappings

Pressure extraction: summary

Poisson

Need for a simple-connected & simple geometry domain

↓

No masked areas (e.g. corrupted/unavailable data region)

NS momentum

Suffers of error propagation

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Sub-division of the integration domain to reduce it

Both have strong dependence on the boundary condition (which and where)

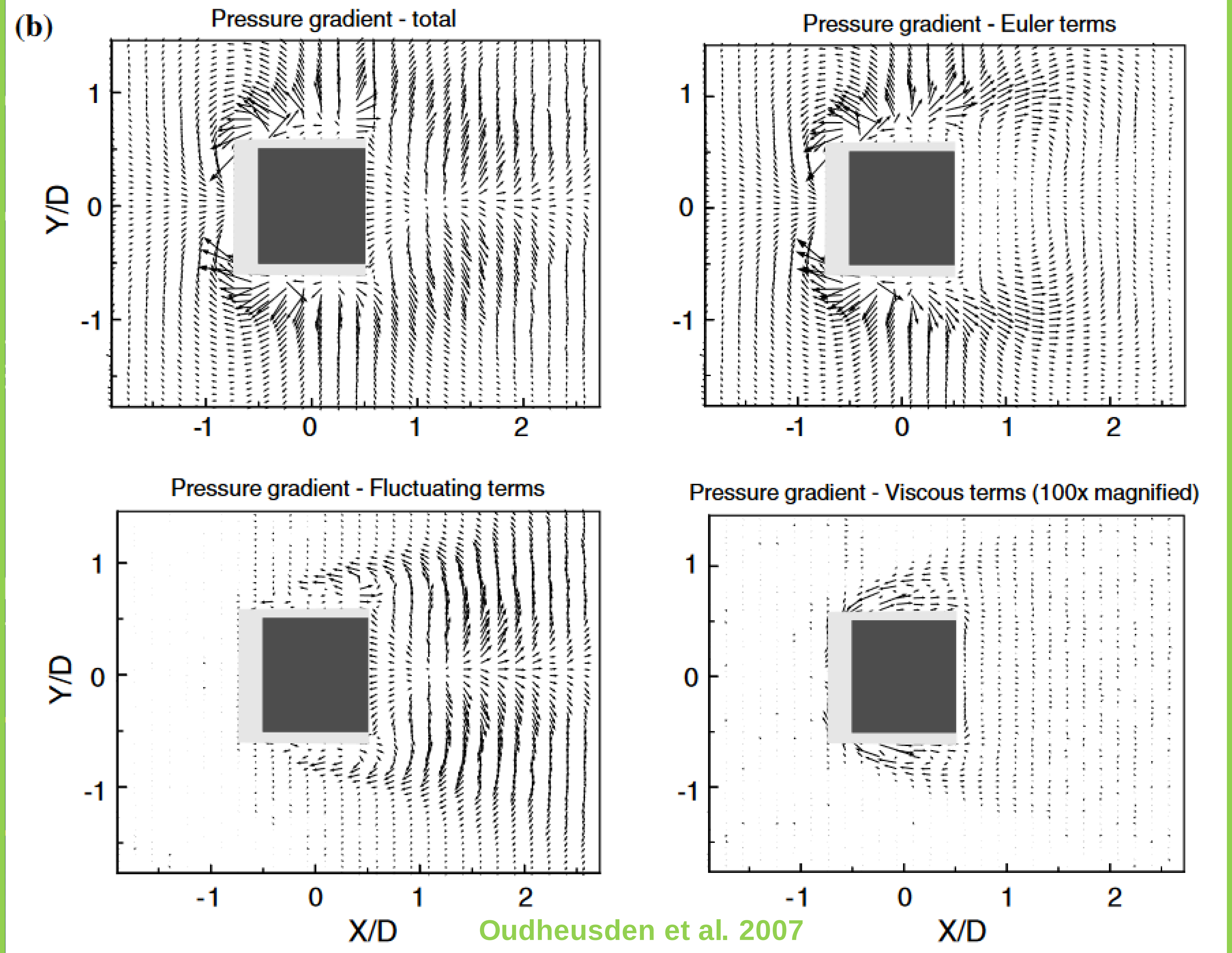
Pressur … roaches

P

- Hp: adequ … time (quas
- Synthetic … ient

$$\frac{\partial < u}{\partial t} \quad \ldots \quad ') + \mu\nabla^2\overline{\boldsymbol{u}}$$

No need

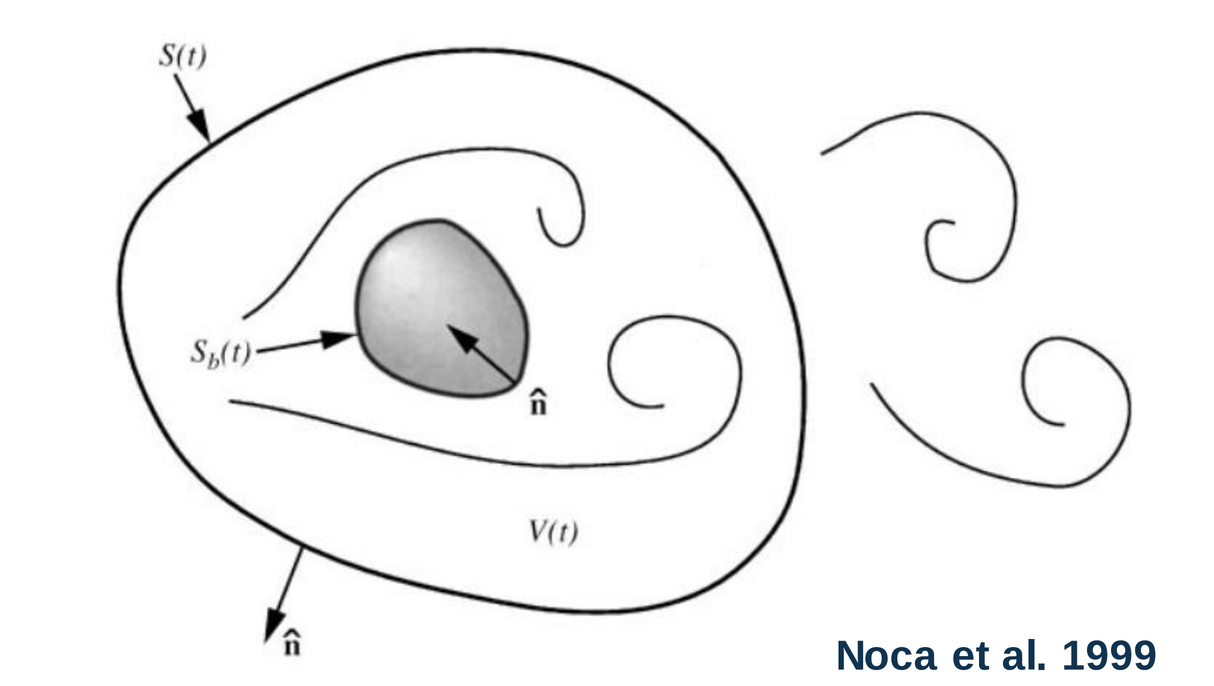


Oudheusden et al. 2007

Loads extraction: principles

Control-volume approach: balance of the NS momentum equation on a domain surrounding the body

- Momentum-based methods (integral form): pressure is needed
- Vorticity-based methods: pressure is analytically eliminated



Noca et al. 1999

Loads extraction: momentum-based

- NS integral momentum equation:

$$\boldsymbol{F}(t) = -\boxed{\int_{V(t)} \frac{\partial \rho \boldsymbol{u}}{\partial t} dV} - \boxed{\int_{S(t)+S_b(t)} \rho \boldsymbol{u}(\boldsymbol{u} \cdot \boldsymbol{n}) dS} + \boxed{\int_{S(t)} (-p\boldsymbol{n} + \boldsymbol{\tau} \cdot \boldsymbol{n}) dS}$$

Volume integral acceleration

Momentum flux across the contour

Total force (pressure + viscous stresses)

Pressure is needed on the contour: (differential) momentum integration

Loads extraction: vorticuty-based

Fluid-dynamic impulse method (Batchelor, 1967): no pressure needed

- Hp: the control volume has to include all the vorticity in the domain

Momentum-based impulse method, (Noca, 1997)

- Vorticity is integrated on surfaces

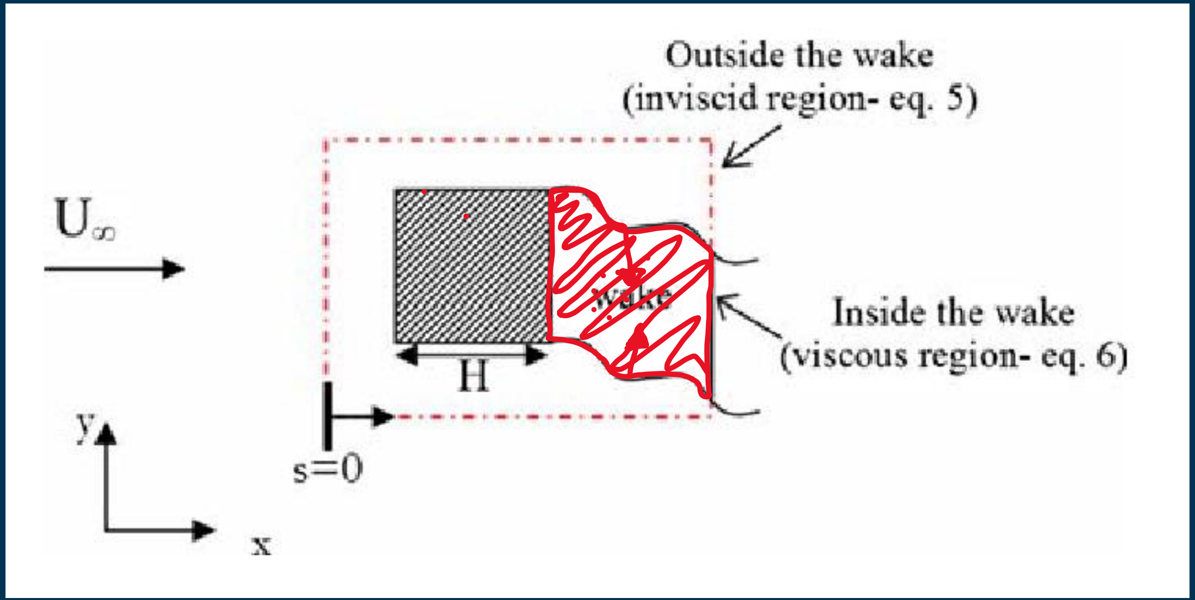
Flux equation impulse method, (Noca, 1997)

- Only contains surface integrals (Hp: $\boldsymbol{\nabla} \cdot \boldsymbol{u} = 0$)

Example: loads on square prism

The flow around a square cylinder was investigated to study the time-varying loads by means of:

- Control-volume approach
- Spatial integration for pressure gradient
- Time-resolved PIV (high repetition rate laser)



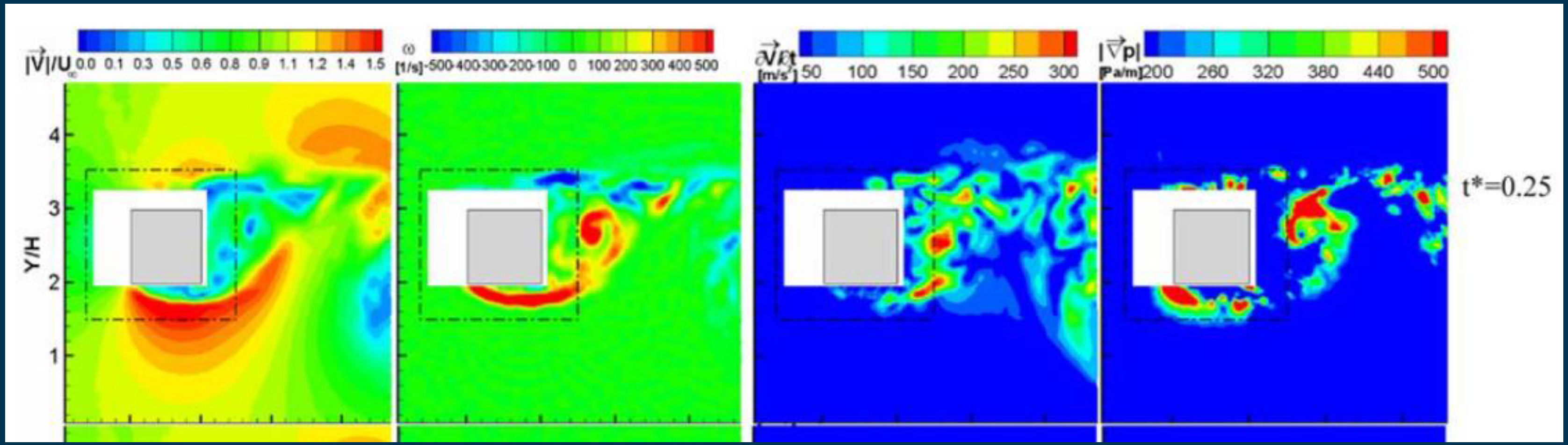
Example: loads on square prism

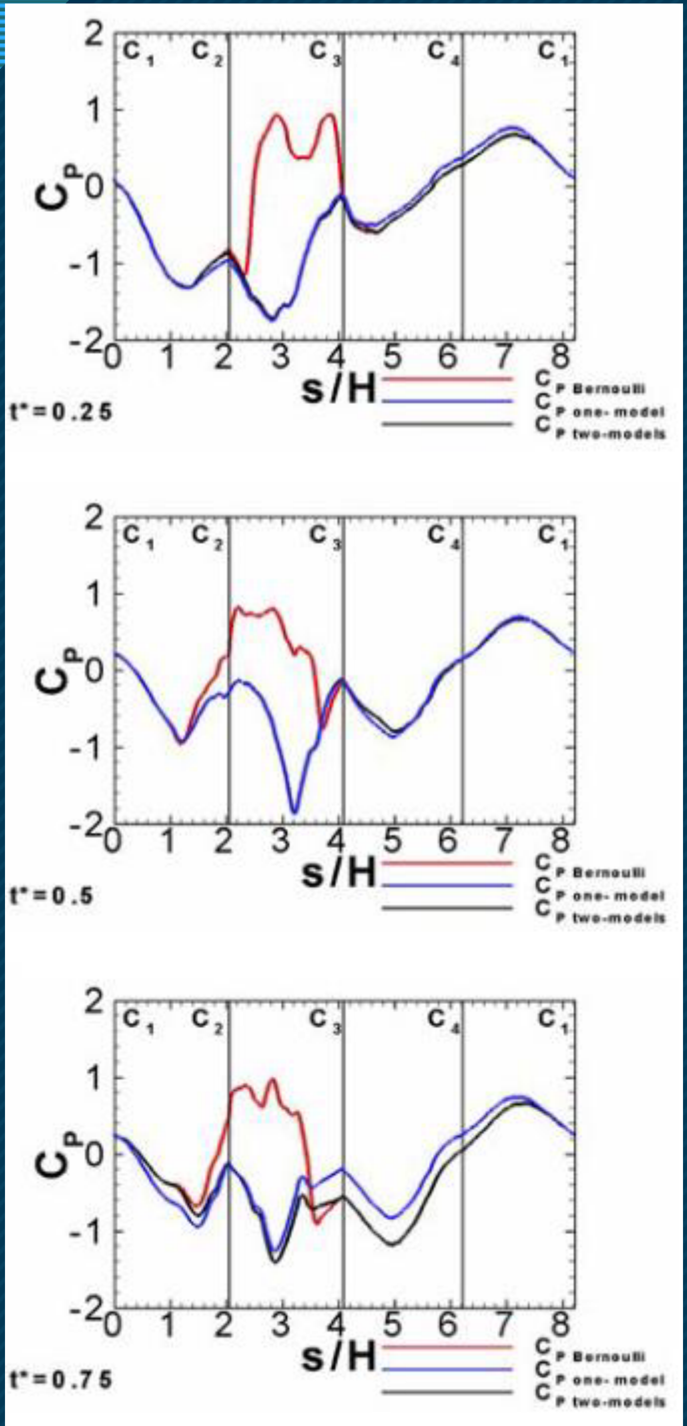
Results:

- Far from the body and outside the wake, the pressure reproduces the velocity pattern

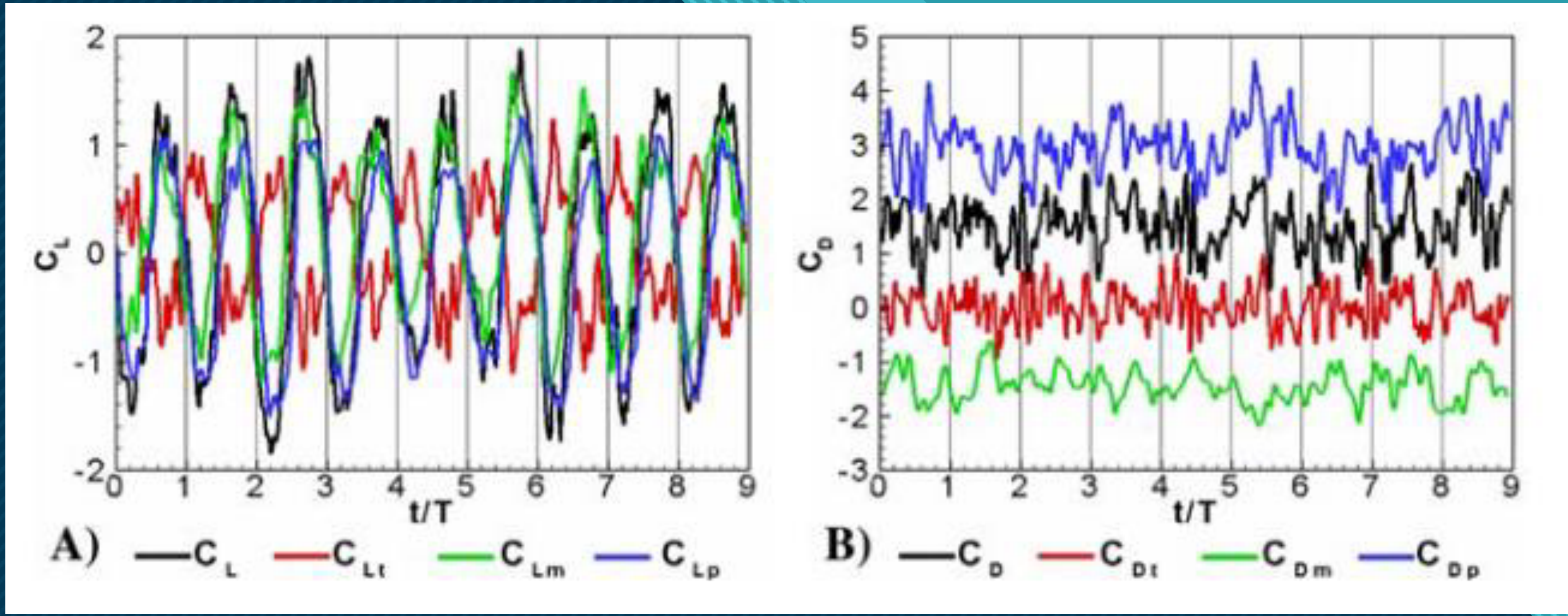
- Alternating value of the pressure in phase opposition on the upper and down sides

- Unsteady lift force fluctuating at half the vortex shedding frequency





$$F(t) = \boxed{-\int_{V(t)} \frac{\partial \rho u}{\partial t} dV} - \int_{S(t)+S_b(t)} \boxed{\rho u(u \cdot n) dS} + \int_{S(t)} \boxed{(-pn + \tau \cdot n) dS}$$



Lift and drag coefficients are obtained:

- Integration of the momentum equation terms along the control surface
- Integration of the unsteady term within the control volume

Error and uncertainty sources