Nonintrusive determination of aerodynamic pressure and loads from PIV velocity data

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TU Delft
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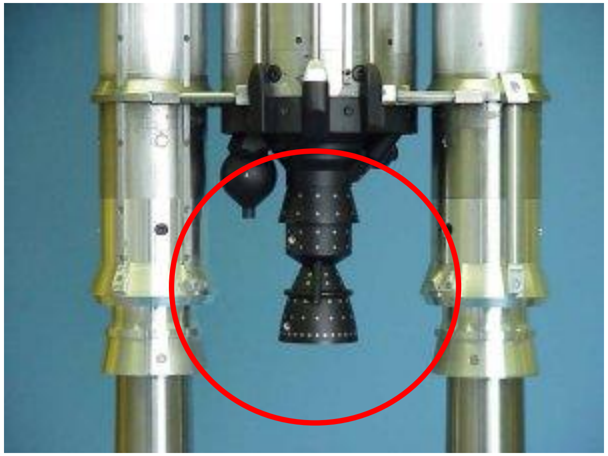
Background: Classical procedures for pressure and load measurement

Pressure: surface pressure sensors and flow probes

Loads: mechanical balance systems

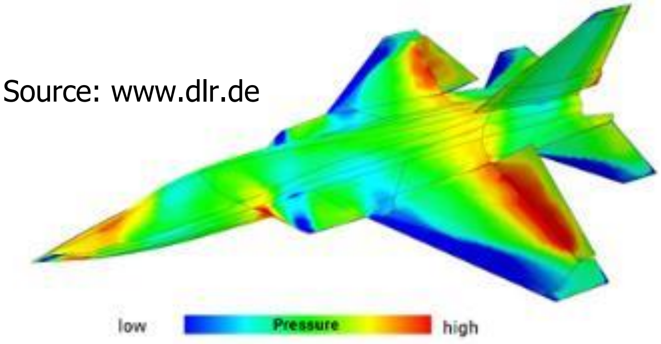
Features:

- Reliable & established
- Expensive (system complexity)
- Intrusive
- Either localized or global
- Low spatial resolution
- High temporal resolution



Non-intrusive optical pressure/load measurement

Source: www.dlr.de



Pressure Sensitive Paint (PSP)

- Surface pressure

PIV/PTV-based pressure measurement: "pressure from velocity"

PIV = Particle Image Velocimetry

PTV = Particle Tracking Velocimetry

Attractive Features:

- Flow-field (+surface) pressure
- Tuneable sensitivity
- Non-intrusive
- No (model or probe) instrumentation required
- Flow + pressure: FSI & aeroelasticity; aeroacoustics

Outline

1. **Working Principles**
2. **Applications (aerospace domain)**

Part 1

Working Principles

Velocimetry-based pressure measurement

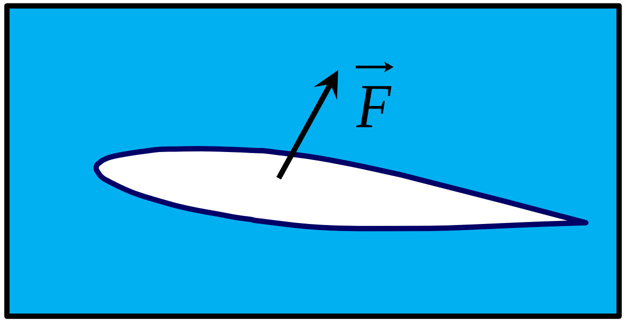
Pressure/loads from velocity: basic operating principle

1. **Pressure gradient from momentum equation:** $\nabla p = -\rho \frac{D\mathbf{u}}{Dt} + \mu \nabla^2 \mathbf{u}$

2. **Pressure field from spatial integration:** $p = \iint \nabla p \, dA$

3. **Integral loads from control volume formulation:**

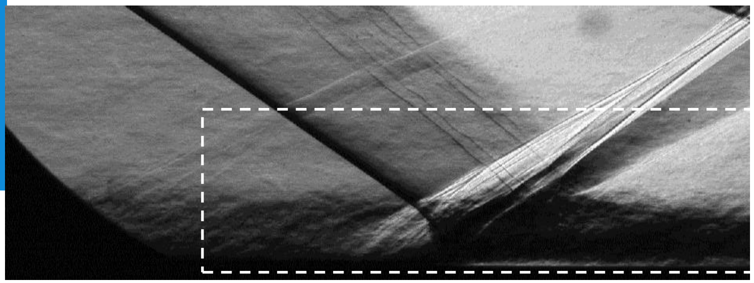
$$\mathbf{F}(t) \approx -\underbrace{\iiint_V \frac{\partial \rho \mathbf{u}}{\partial t} dV}_{\text{Acceleration term}} - \underbrace{\iint_S \rho \mathbf{u}\mathbf{u} \cdot \mathbf{n} \, dS}_{\text{Momentum flux term}} - \underbrace{\iint_S p \, \mathbf{n} \, dS}_{\text{Pressure term}}$$

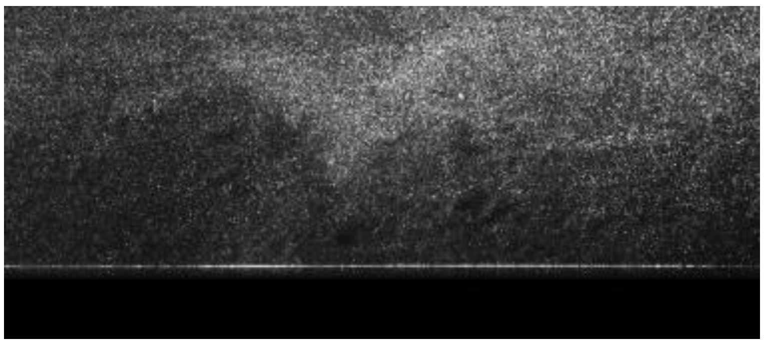


Review publications:

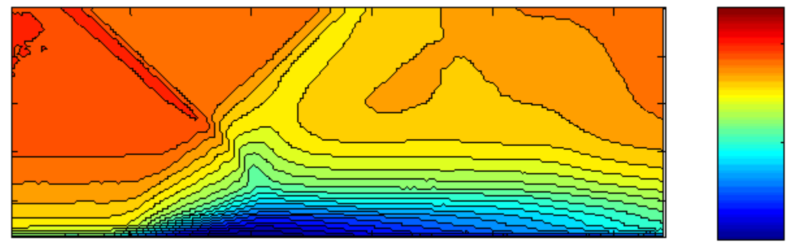
- Van Oudheusden (Meas.Sci.Technol. 2013) - pressure
- Rival & Van Oudheusden (Exp.Fluids 2017) - loads

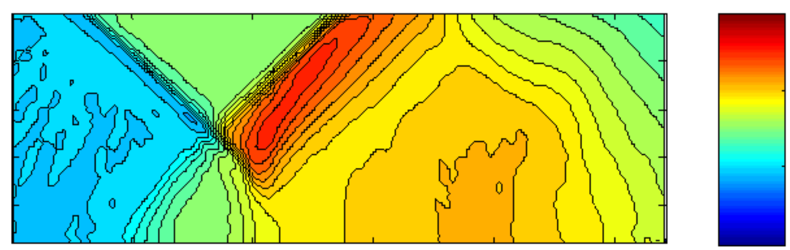
PIV-based pressure procedure





Mach = 1.6 shock-wave boundary-layer interaction
(Van Oudheusden and Souverein 2007)





1. **PIV image recording**
2. **image interrogation**
3. **pressure integration**

Visualisation-based pressure determination

A (pre-)historical example: Schwabe 1935 (!)

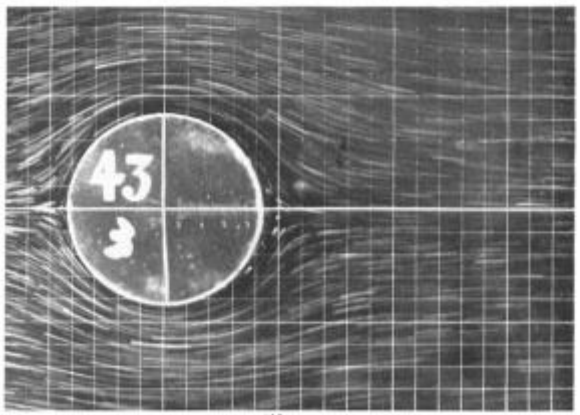


Abb. 5a.

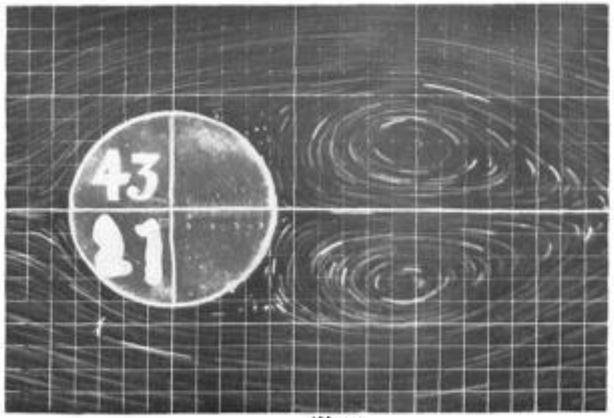


Abb. 5e.

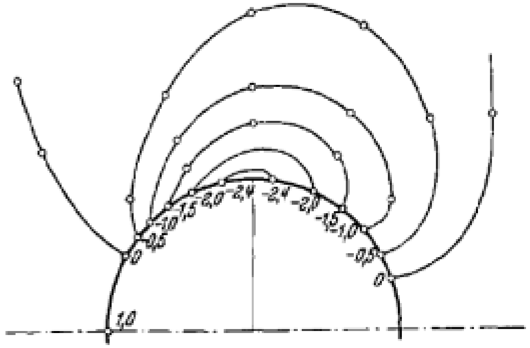


Abb. 7a.

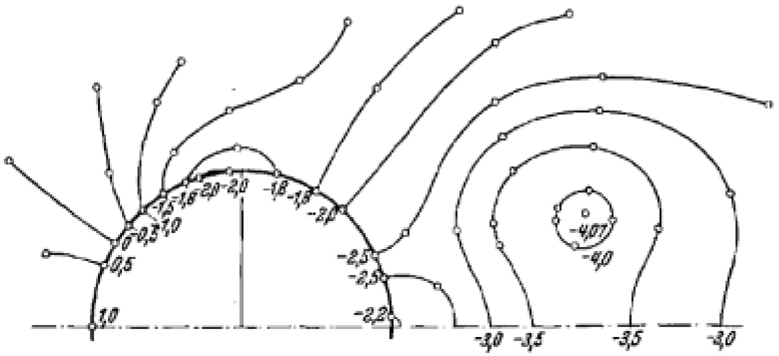


Abb. 7b.

Abb. 7a, 7b. Linien gleichen Druckes. *a* nach Abb. 5a, *b* nach Abb. 5e.

Schwabe M (1935) Über die Druckermittlung in der nichtstationären ebenen Strömung - *Ing. Archiv*

Visualisation-based pressure determination

Developments towards a digital implementation

Progress is enabled by advances in digital camera hardware, image processing tools and numerical algorithms

Early steps:

- Imaichi and Ohmi (1983) applied a numerical processing of photographic flow-visualization data of two-dimensional cylinder flows

Real progress after the introduction of Digital PIV (DPIV, Willert & Gharib, 1991):

- Jakobsen et al (1997) and Jensen et al. (2001) used PIV to determine acceleration and pressure in water wave phenomena
- Baur and Köngeter (1999) investigated pressure variations in vortical structures
- Gurka et al. (1999): time-average pressure in a nozzle flow and an air jet

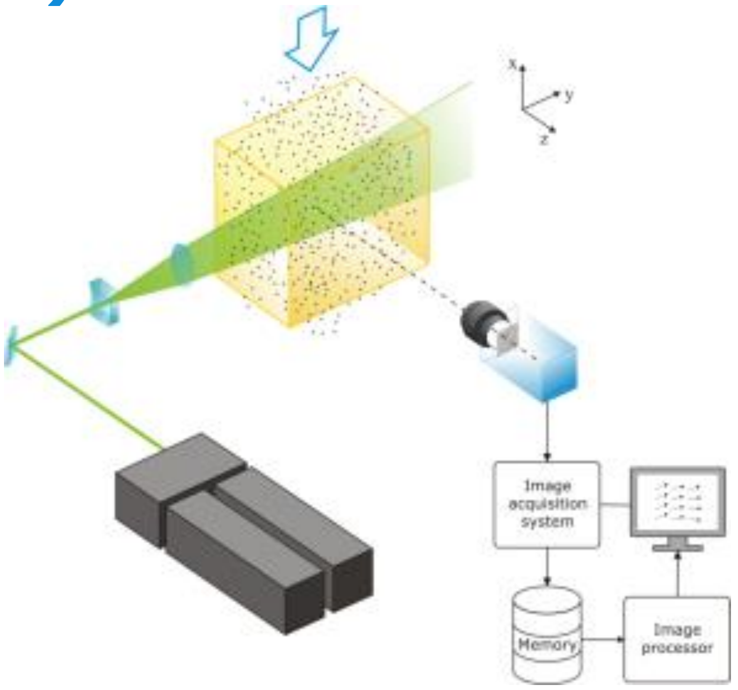
So, basically the technique is about 20 years old

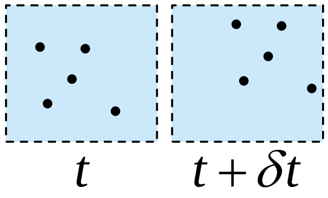
Particle Image Velocimetry (PIV)

Planar PIV (2C or 3C-stereo)

Basic working principle:

1. Flow is seeded with small particles
2. Illumination by thin laser sheet (pulsed)
3. Two image frames are captured at small time interval (= pulse separation δt)
4. Image interrogation: cross-correlation of frame sections ("interrogation windows") provides local average particle displacement
5. local flow velocity = part.displacement / δt





an "interrogation window"

Typical current PIV system capabilities:

- pulse separation δt down to 1 μs
- Repetition rate up to 10 kHz

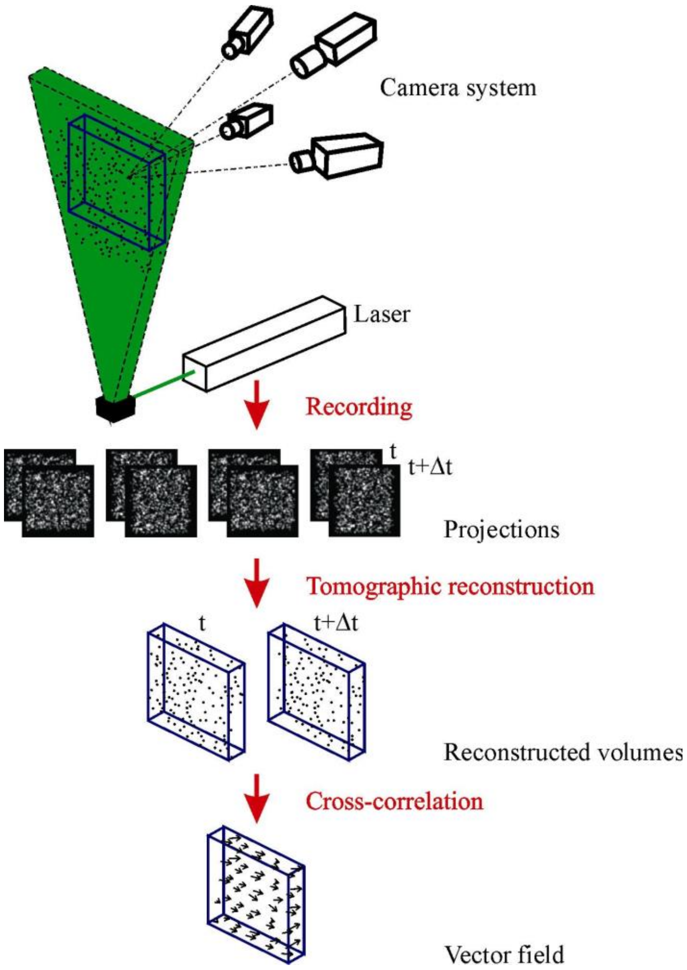
Volumetric PIV

Tomographic PIV

Extension of stereoscopic PIV:

1. Volumetric illumination
2. Simultaneous recording from multiple views → "projections" (typical 4)
3. Tomographic reconstruction of volumetric "particle" distribution
4. 3D cross-correlation → **3D-3C** velocity data

- Tomo-PIV has severe volumetric limitations (~100 cm^3 in air) + large processing time
- Recent improvements by using volumetric particle tracking methods



(Elsinga et al, Exp. in Fluids, 2006)

PIV-based "pressure measurement"

$$\nabla p = -\rho \frac{D\mathbf{u}}{Dt} + \mu \nabla^2 \mathbf{u}$$

with:

$$\frac{D\mathbf{u}}{Dt} = \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u}$$

viscous term (negligible)

material derivative = flow acceleration

Requirements on velocity measurement

- **Instantaneous pressure determination** in unsteady flows: requires acceleration data (time-resolved or "multiple-pulse" PIV)
  - pulse separation δt governs velocity measurement
  - time separation Δt (~repetition rate) governs acceleration measurement
- **Mean pressure** (or steady flow): velocity mean/statistics sufficient
- **Pressure in 2D flow**: planar velocity data sufficient (2C-PIV)
- **Pressure in 3D flow**: volumetric velocity data needed (3D-3C-data)

Accuracy of material derivative determination

Effect of time separation Δt

$$\frac{du}{dt}(t) \approx \frac{u(t+\Delta t) - u(t)}{\Delta t}$$

Error sources:

1. **Truncation error**

   (result of discretization)

   NB: τ and U are typical time and velocity scales of the flow

$$\varepsilon_{trunc} \sim \Delta t \frac{U}{\tau^2}$$

opposite effects of time separation

2. **Precision error**

   propagation of velocity measurement uncertainty ε_u

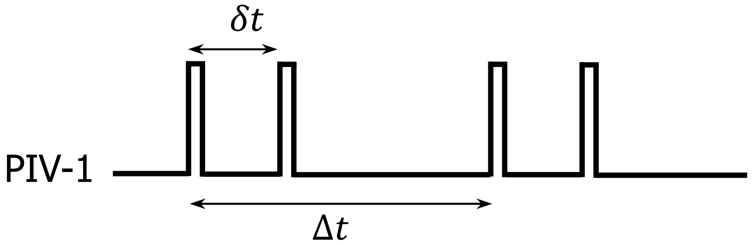
$$\varepsilon_{pr} \sim \frac{\varepsilon_u}{\Delta t}$$

typically $\Delta t / \delta t$ of the order 5 to 10

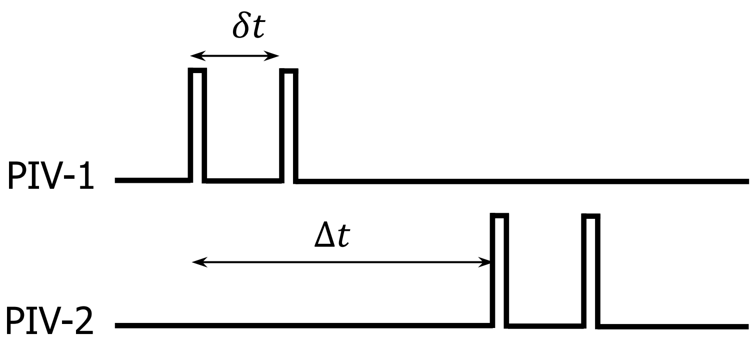
NB: error can be further reduced by using time-series data

Timing strategies (hardware implementation):

- **Time-resolved double-pulse:**
  - Allows independent tuning of pulse separation δt and time separation Δt
  - Requires high repetition rate (~ kHz)
  - Minimum time separation sets limit on flow speed (~ 25 - 50 m/s)



- **Multiple-pulse (or dual PIV):**
  - Suitable for high speed flow
  - Small time separation achieved by delay between two independent PIV systems; no high repetition rate required!
  - Optical separation of the PIV systems (e.g. by wavelength or polarization)

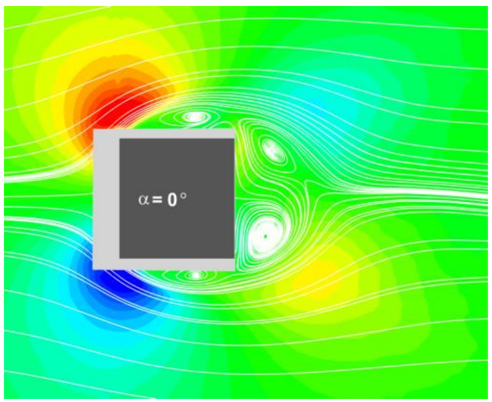


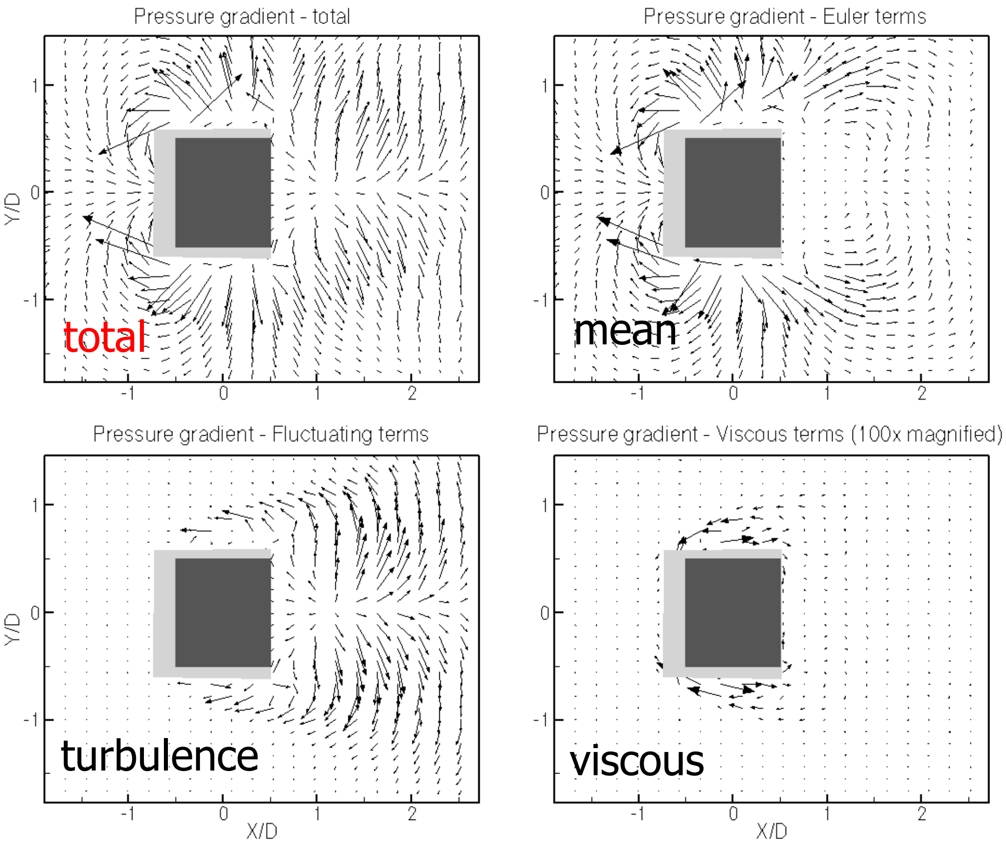
Reynolds-averaging for mean pressure

Mean pressure gradient from Reynolds-averaged momentum equation:

$$\nabla \bar{p} = -\rho(\bar{\mathbf{u}} \cdot \nabla \bar{\mathbf{u}} + \nabla \cdot \overline{\mathbf{u}'\mathbf{u}'}) + \mu \nabla^2 \bar{\mathbf{u}}$$

contributions from: mean flow turbulence viscous





Contributions to the mean pressure gradient for the flow around a square-section prism (Re_D = 20,000)

Note: viscous terms negligible

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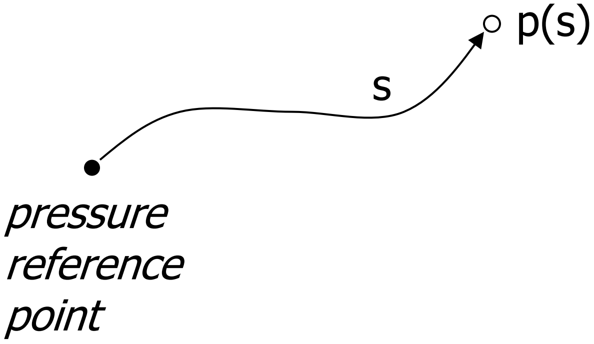
Pressure-gradient integration approaches

Spatial integration:

$$p(\mathbf{s}) = p(\mathbf{s}_{\text{ref}}) + \int_{\mathbf{s}_{\text{ref}}}^{\mathbf{s}} \nabla p \cdot d\mathbf{s}$$



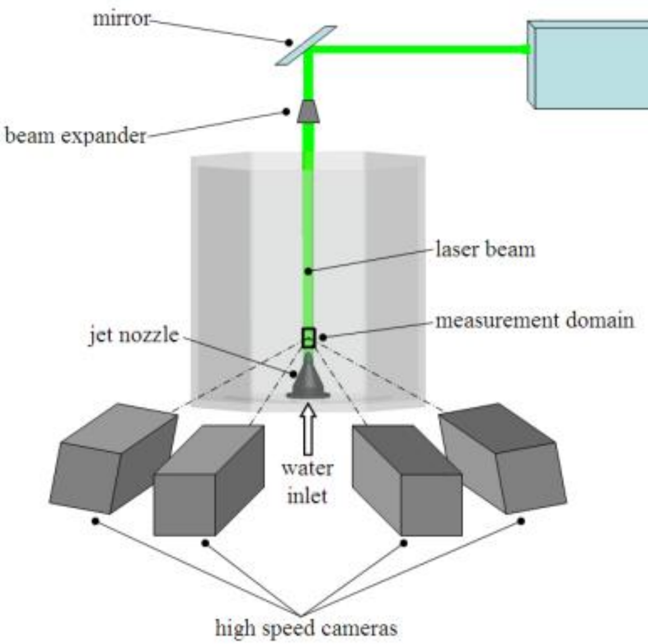
Uniqueness:

- Pressure value can be path-dependent due to pressure-gradient inconsistencies (measurement errors or incomplete velocity information)
- Multi-path integration or marching-schemes with weighted averages
- Poisson-equation approach (equivalent to global error minimization)

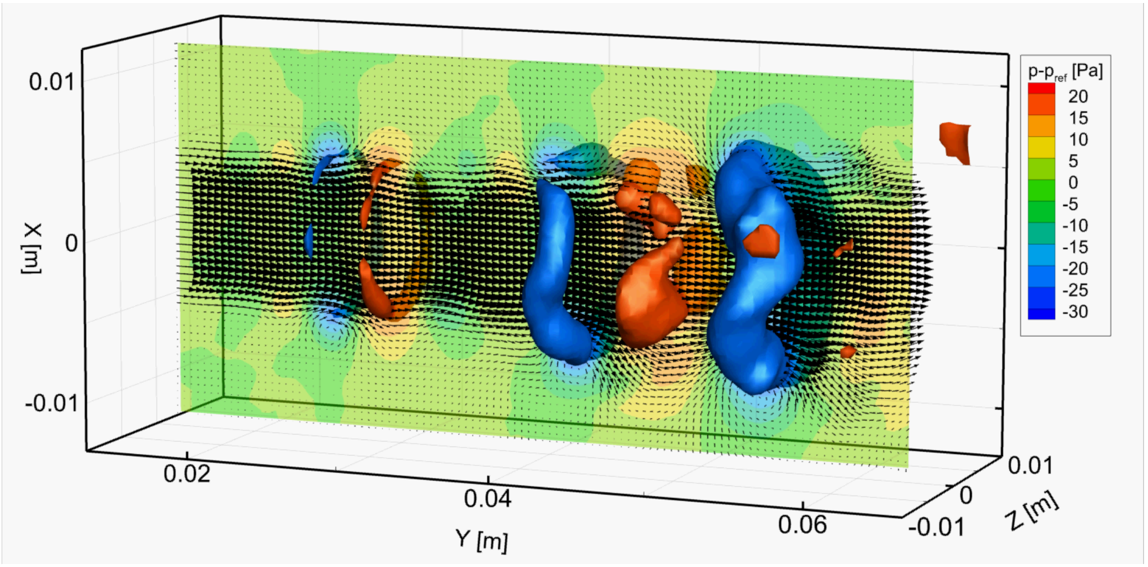
$$\nabla^2 p = \nabla \cdot f(\mathbf{x}, t) \quad \Leftrightarrow \quad \min_p \int_S \left\| \nabla p - f(\mathbf{x}, t) \right\|^2 dS$$

Example: 3D pressure field of low-Re jet in water

3D characterization of a transitional jet using time-resolved tomo-PIV



Formation and breakup of ring vortices
pressure field animation
(courtesy of: Matteo Novara)



Nozzle exit diameter: 10 mm
Exit velocity: 0.1 – 2.5 m/s
Meas. domain size: 3 x 3 x 5 cm^3
Acquisition rate: 1 kHz

(Violato et al. 2011)

Part 2

Applications in high speed flows

Extension to compressible flows

Axisymmetric base flows

Extension to compressible flow

Governing relation: (with viscous term neglected)

- momentum equation: $\nabla p = -\rho \frac{D\mathbf{u}}{Dt}$ but with variable density!

Closure procedure: (Van Oudheusden et al. 2006)

- equation of state: $\rho = \frac{p}{RT}$
- constant total temperature: $c_p T + \frac{1}{2}\|\mathbf{u}\|^2 = \text{cst.}$

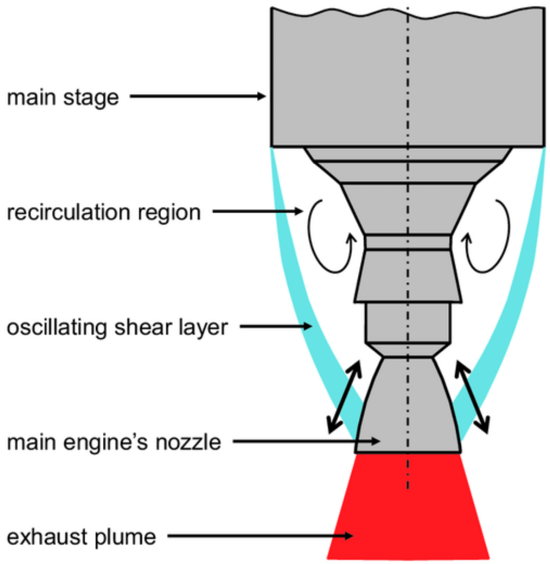
$$\left.\begin{array}{l} \rho = \frac{p}{RT} \\ c_p T + \frac{1}{2}\|\mathbf{u}\|^2 = \text{cst.} \end{array}\right\} \rho = \frac{p}{R \cdot T(\|\mathbf{u}\|)}$$

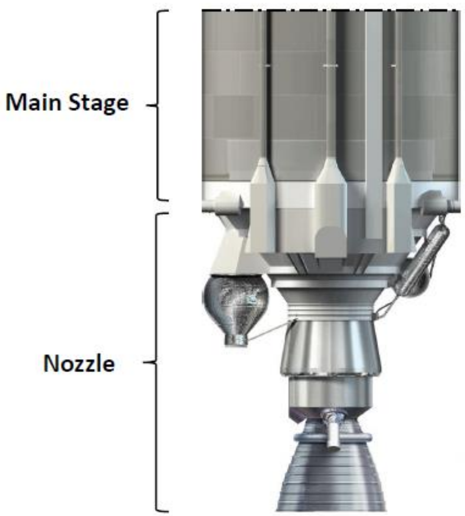
Explicit formulation for the pressure gradient: $$\frac{\nabla p}{p} = \nabla(\ln p) = \frac{1}{R \cdot T(\|\mathbf{u}\|)} \cdot \frac{D\mathbf{u}}{Dt}$$

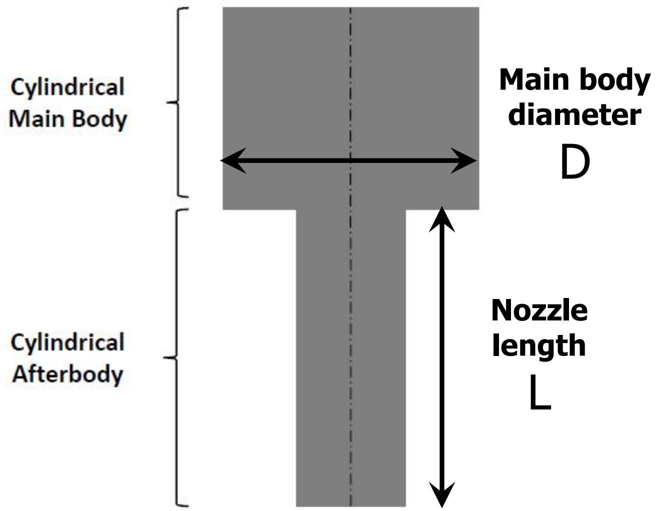
Axisymmetric base flows

Relevance:

- Background: transonic buffet in launchers
- Unsteady shear layer reattachment
- Simplification: generic (axisymmetric) test geometries







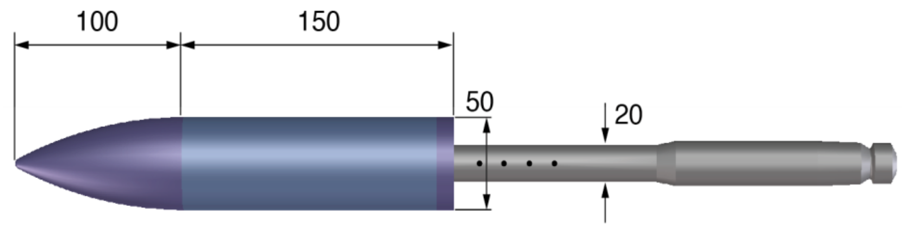
(Scharnowski, 2014)

(Van Gent, 2018)

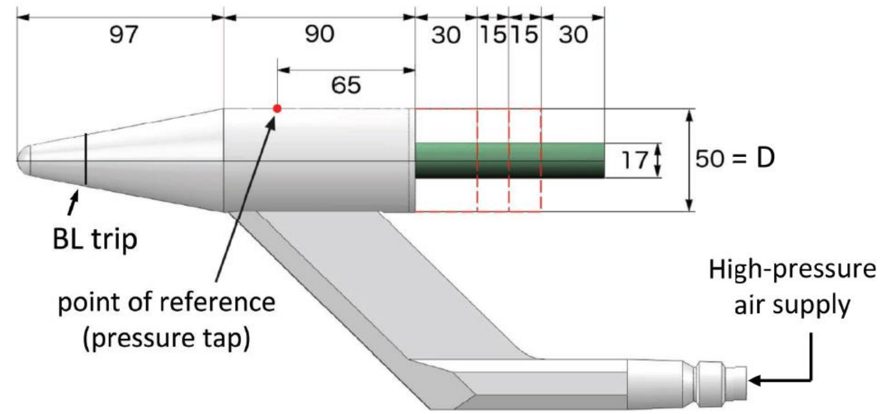
Base flow investigations

Experimental models:

- Rear-sting mounted model

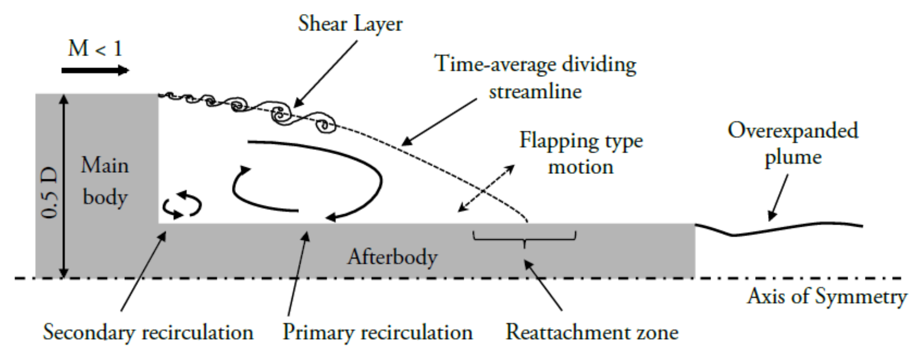


- Side-sting mounted model with exhaust plume simulation (1990’s FESTIP program)



Objectives:

- Unsteady flow behaviour
- Particular interest: pressure on base and afterbody
- Influence of afterbody length and plume presence



Base flow investigations

1. Potential for instantaneous pressure:

- Synthetic test case: method assessment (numerical simulation)
- Instantaneous pressure in low-speed (experimental)
- Idem in high-speed

2. Determination of mean pressure:

- Re-averaged approach for mean pressure
- 2D vs 3D data (is tomo necessary?)
- Application study: base flow with simulated exhaust plume

SEVENTH FRAMEWORK PROGRAMME

PhD of Paul van Gent (various publications; 2015-2018)

Partly funded by FP7 project “NIOPLEX” (2013-2016)

NIOPLEX

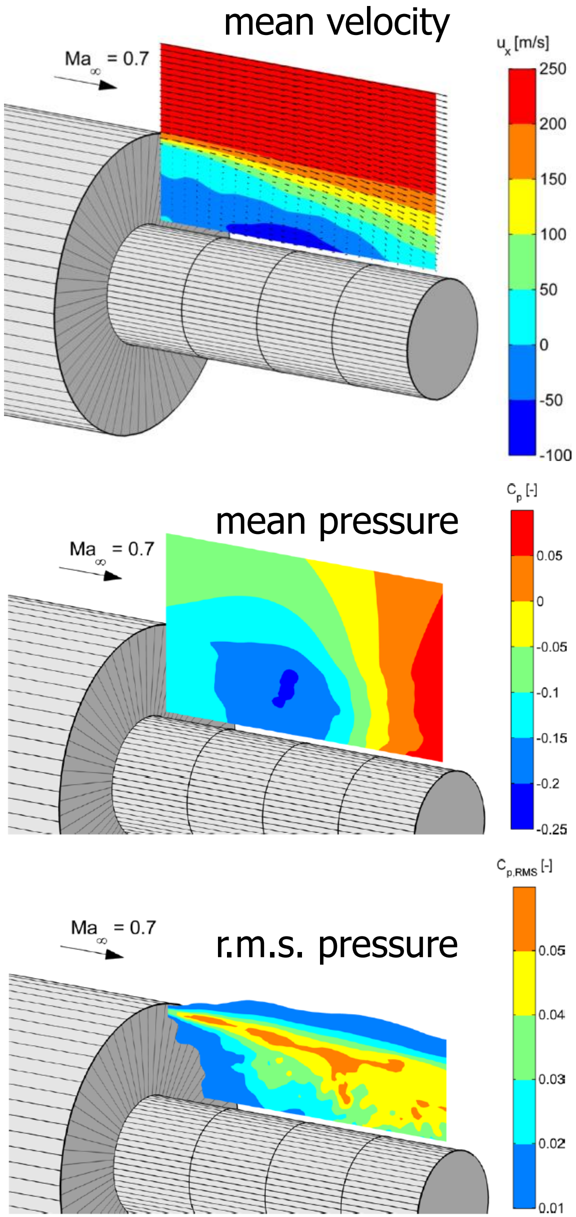
Comparative test case

Methodology:

- Reference data: Zonal Detached Eddy (ZDES) simulation (ONERA) of a transonic base flow (Mach = 0.7)
- The CFD data is processed to construct a "synthetic PIV experiment"
- This comprises sequences of quasi-PIV/PTV data in either <u>time-resolved</u> or <u>multi-pulse</u> (4 pulses) mode

Objectives:

- Assessment of modeling assumptions
- Comparison of different methods (PIV/PTV, time-resolved/multi-pulse, processing schemes)
- Effect of data noise, etc..



(Schneiders et al., 2014)

(Van Gent et al., Experiments in Fluids, 2017)

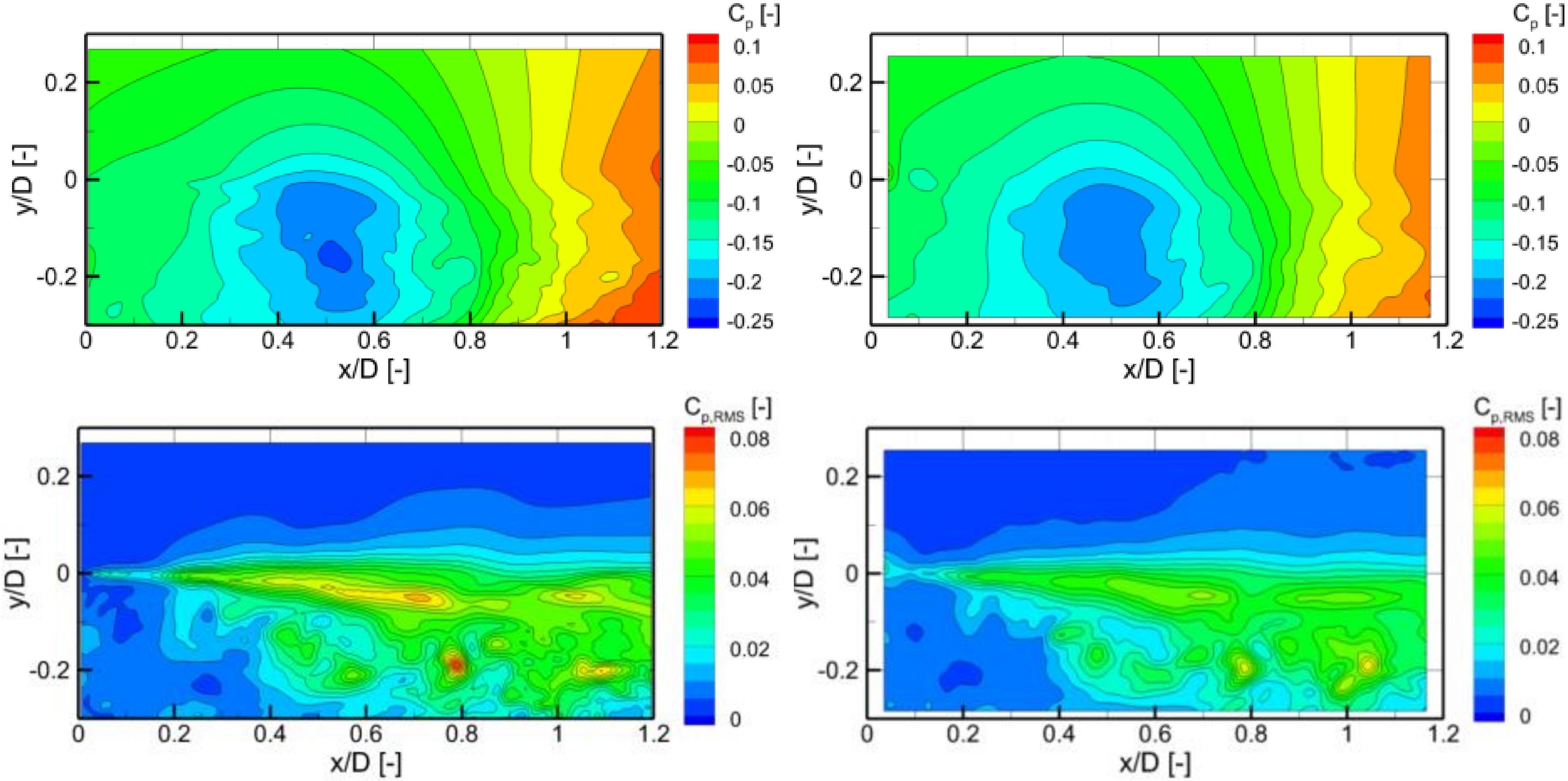
Comparative test case – results

Illustrative results from an earlier study

Reference (CFD) “PIV results”

Mean pressure

Pressure r.m.s.



(Van Gent et al., Lisbon Laser Conf, 2014)

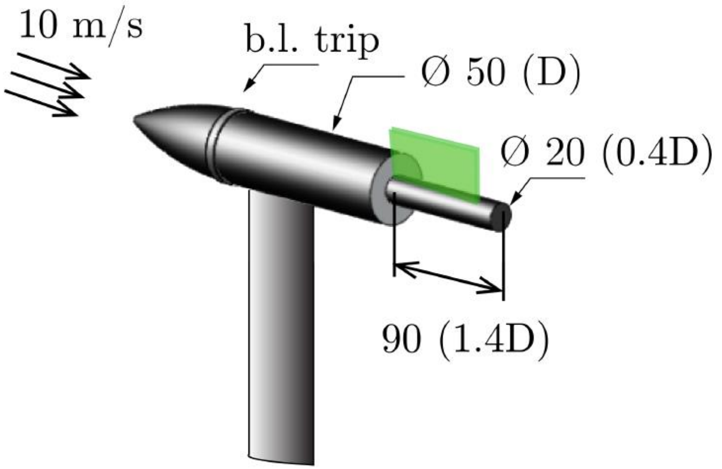
Comparative test case - conclusions

- Modeling assumptions are less relevant than the accuracy of the flow acceleration determination
- All different processing methods allow a good to accurate reconstruction of the pressure (r.m.s. errors <1-2%)
- PTV-based methods can give higher accuracy than PIV-based, due to higher spatial resolution
- Time-resolved data provides the best results, but meaningful pressure can be obtained from multi-pulse (or even single-snapshot) approaches
- Adding (realistic) image noise levels is not prohibitive

Low-speed base flow experiment

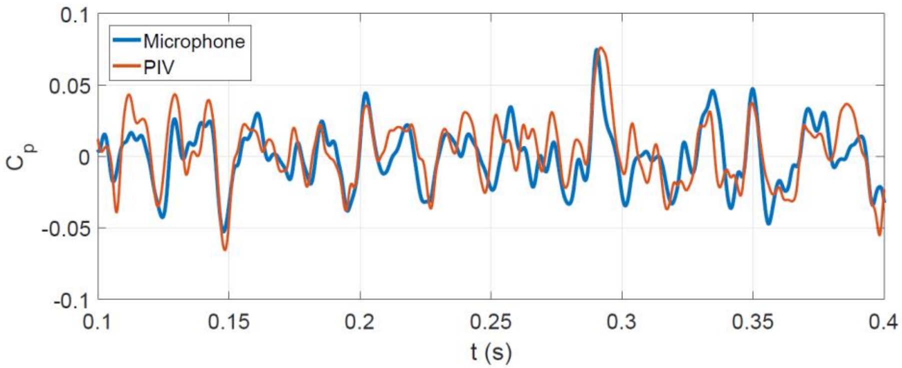
Experimental set-up:

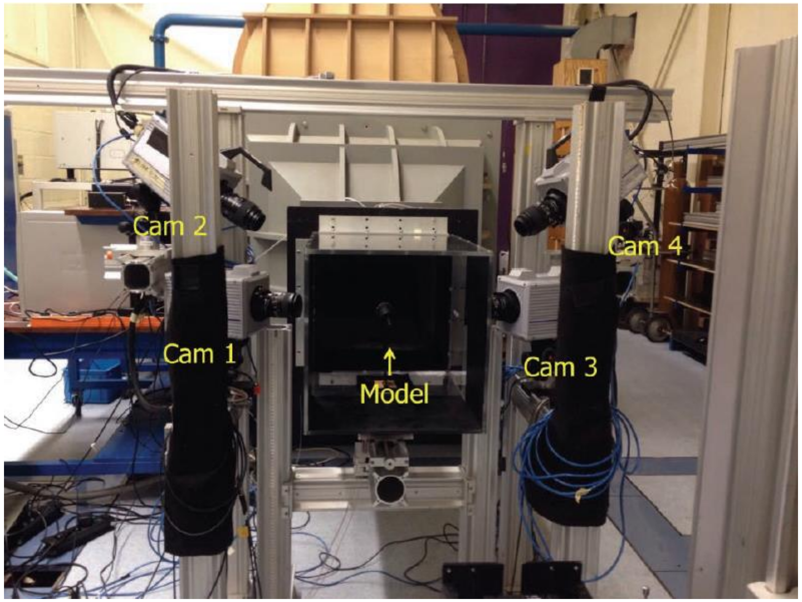
- Flow speed: 10 m/s
- PIV: 4-camera thin-tomo volume (75 mm x 35 mm x 3.5 mm)
- Acquisition rate 10 kHz (**time-resolved**)
- Reference pressure: microphones (6)



Data processing:

- Flow acceleration is computed from tracks of 25 subsequent PIV fields

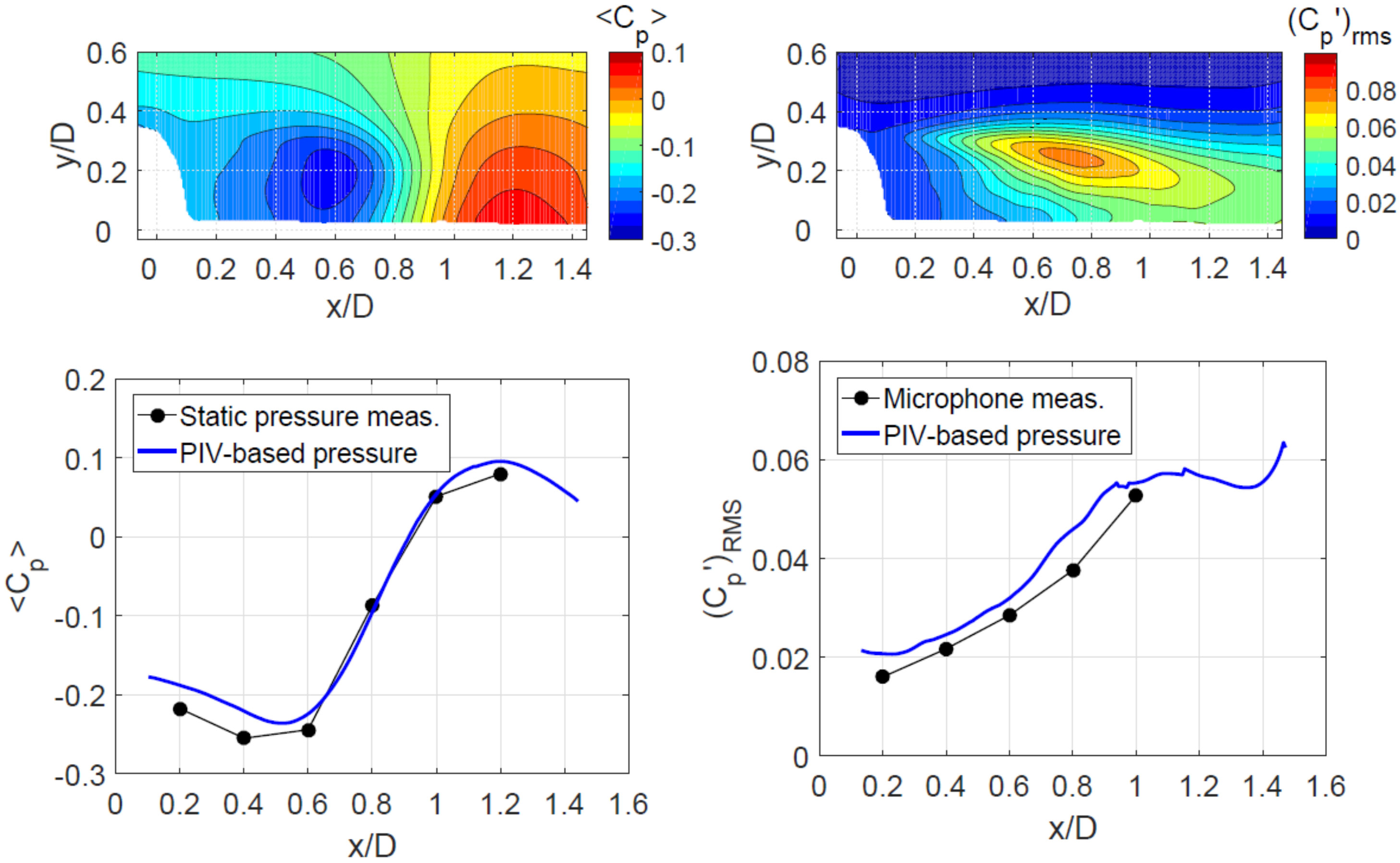




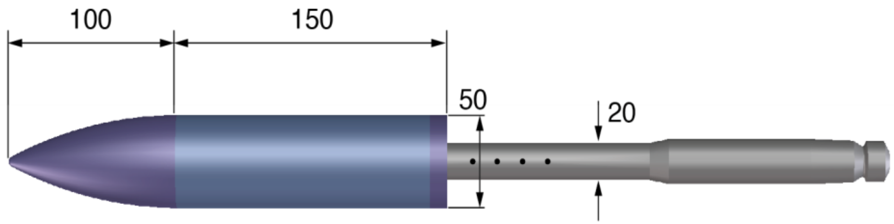
Low-speed base flow experiment

Results:

- Good agreement between PIV-based and reference (microphone) pressure



High-speed base flow experiment

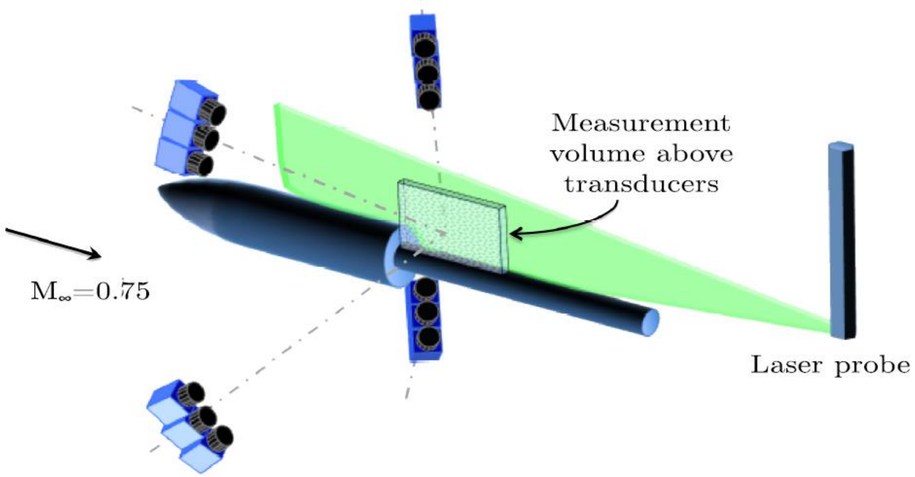


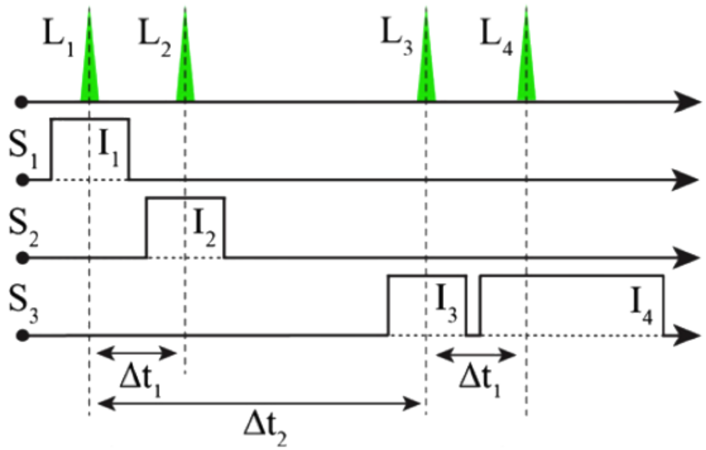
Model:

- Rear-sting-mounted model
- Flow speed: Mach = 0.75
- Pressure: 4 Endevco transducers

PIV set-up:

- PIV strategy: **four-pulse tomographic**
- 3 independent tomographic PIV systems
  (2-laser, 12-camera system, Lynch & Scarano 2014)
- PIV volume: 65 mm x 45 mm x 3.5 mm





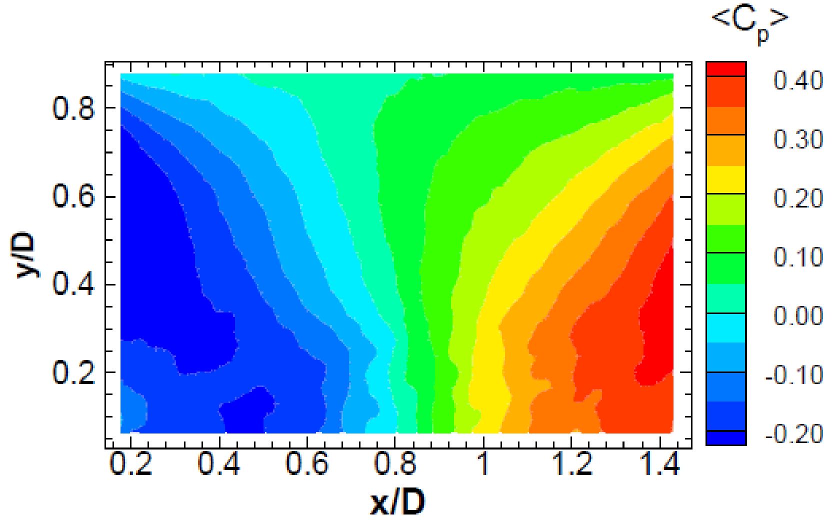
Δt_1 = 2.5 μs; Δt_2 = 5-10 μs

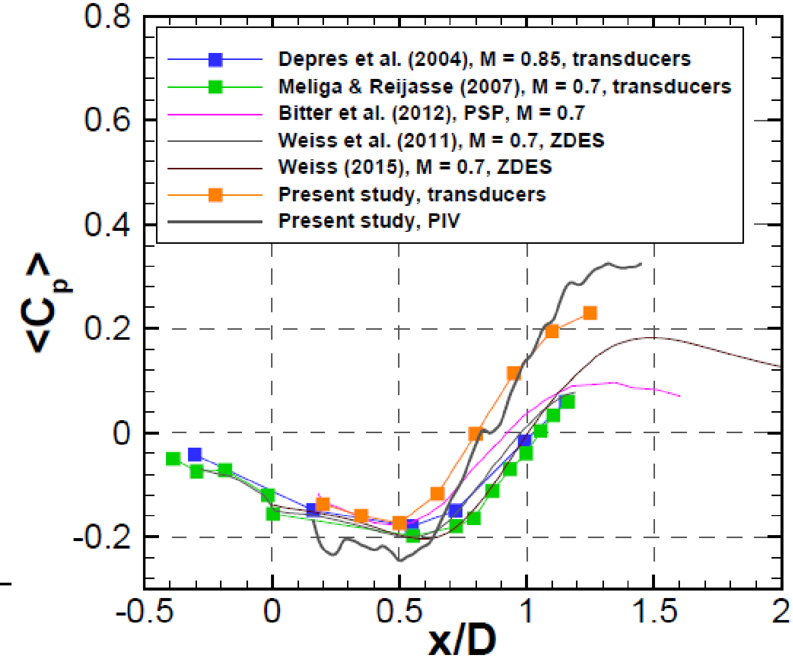
(Van Gent, PhD thesis, 2018)

High-speed base flow experiment

Results for the mean pressure:

- Good agreement between transducer and PIV-based pressure
- Reasonable agreement with other experiments and numerical simulations (differences in exact configuration, flow conditions, blockage, etc.)





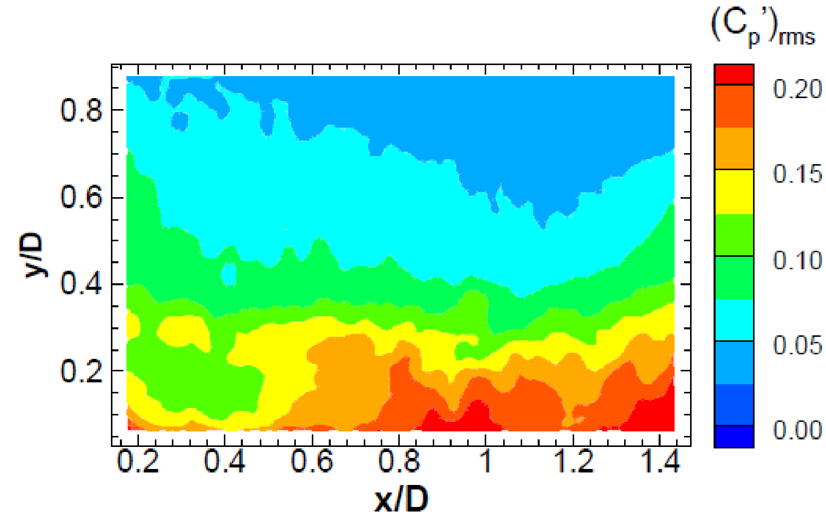
High-speed base flow experiment

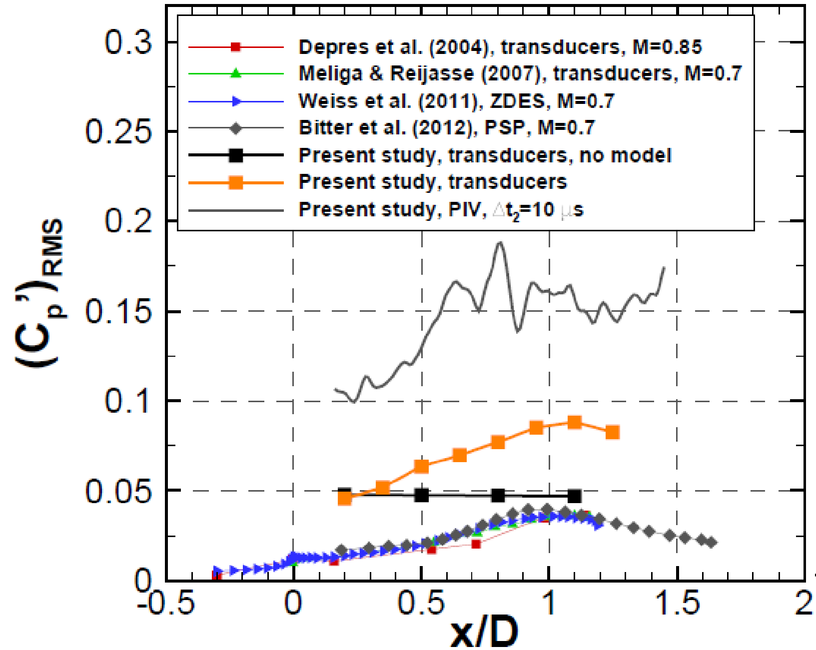
Results for the r.m.s. pressure:

- Poor agreement between PIV and transducers
- Pressure levels higher than for reference studies (both exp & num)

Possible causes:

- High wind tunnel noise level
- Detrimental effect of discrepancies between the different PIV systems





Mean pressure determination in compressible flow

Reynolds averaging approach

- (Mean) pressure from velocity data using (Re-avg.) momentum equation:

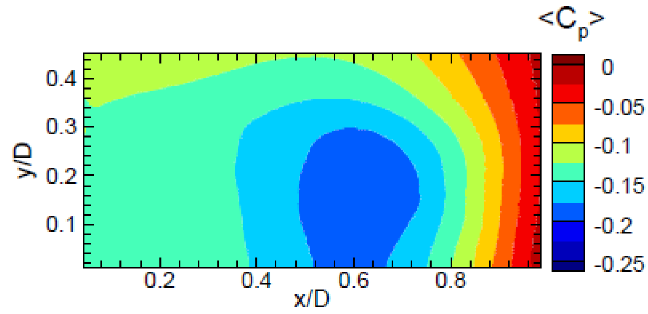
$$\nabla\bar{p} = -\rho[\bar{\boldsymbol{u}}\cdot\nabla\bar{\boldsymbol{u}} + \nabla\overline{\boldsymbol{u}'\boldsymbol{u}'}] + h.o.t.$$

- $h.o.t.$: fluctuations and gradients of density -> are negligible (Van Gent et al. 2018)

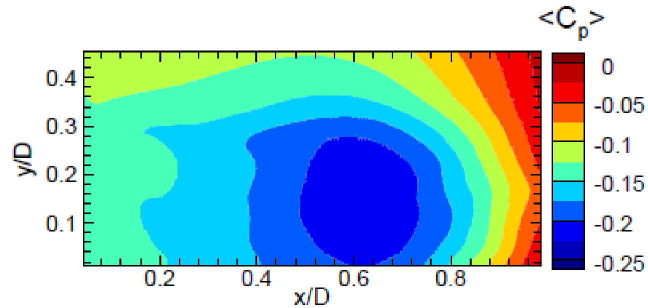
Assesment with synthetic PIV exp. data:

- Contribution of the Reynolds-stresses: ~ 20%
- Contribution of $h.o.t.$: ~ 1 %
- Including Re-stresses reduces r.m.s. error from 17% to 5%

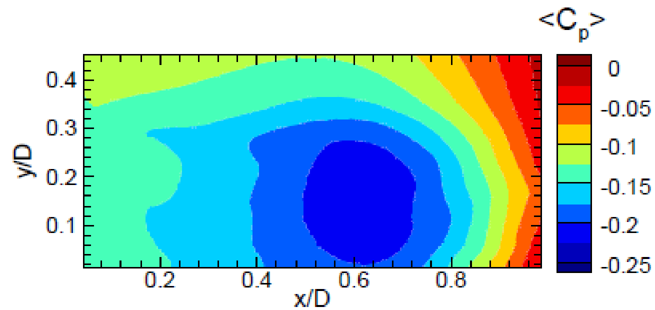
- <u>Tomo vs. planar PIV</u>: 2D-2C and 3D-3C results differ by less than 1%!
- -> planar PIV is "sufficient" in this case (NB: axisymmetric geometry)



(b) Pressure field reconstructed using mean-flow terms



(d) idem + Reynolds-stresses terms



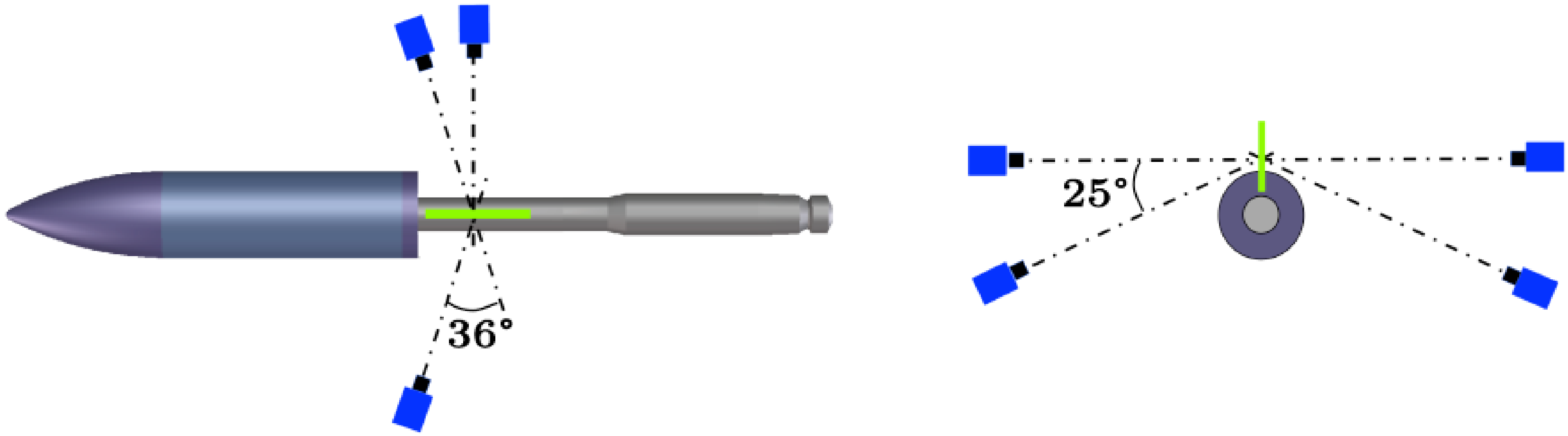
(f) idem + density-gradient terms

(Van Gent et al., Experiments in Fluids, 2018)

Mean pressure: compressible base flow experiments

Experimental set-up

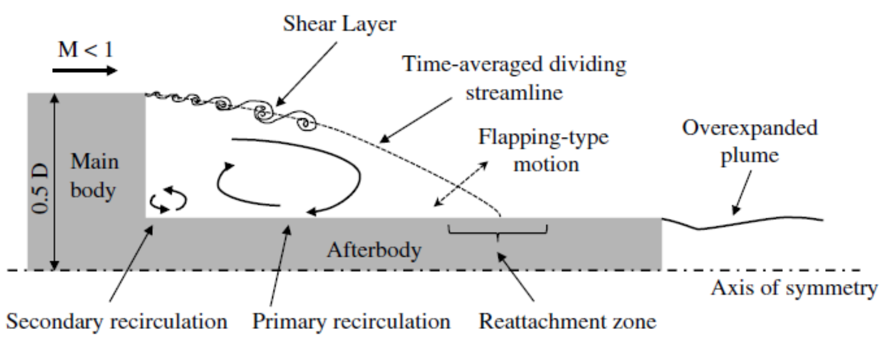
- Rear-sting-mounted model
- Single tomographic PIV system (5 cameras, one in planar configuration)
- Standard **double-pulse** strategy @ 5 Hz repetition rate)
- PIV volume: 85 mm x 50 mm x 5 mm
- Mach number: M = 0.75 (transonic) and M = 1.5 (supersonic)

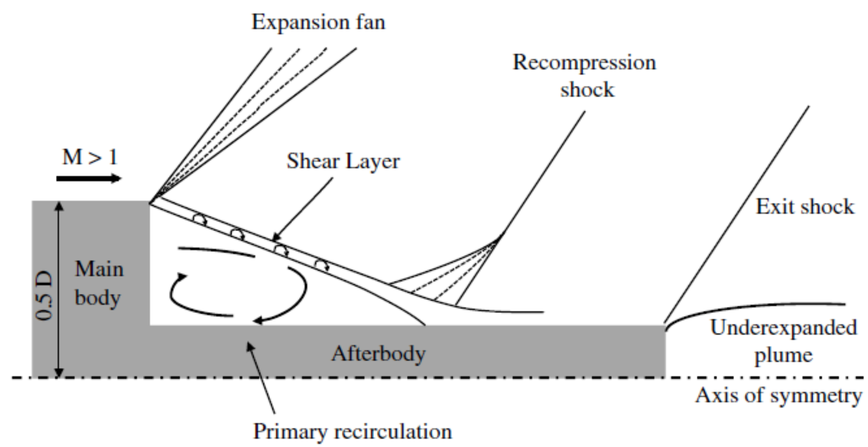


(a) Top-view (b) Back-view

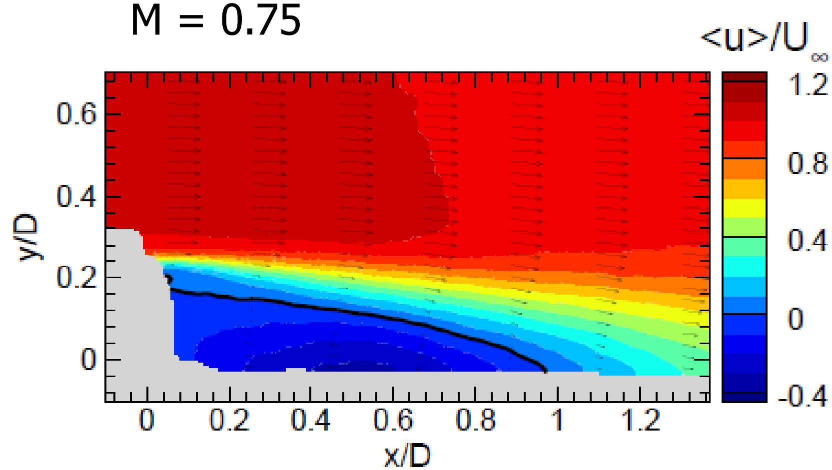
Mean pressure: compressible base flow experiments

Time-average velocity flow fields

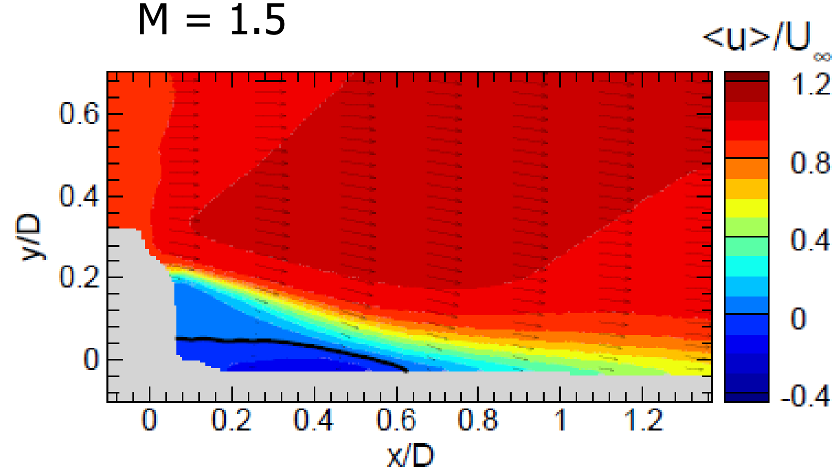




M = 0.75



M = 1.5

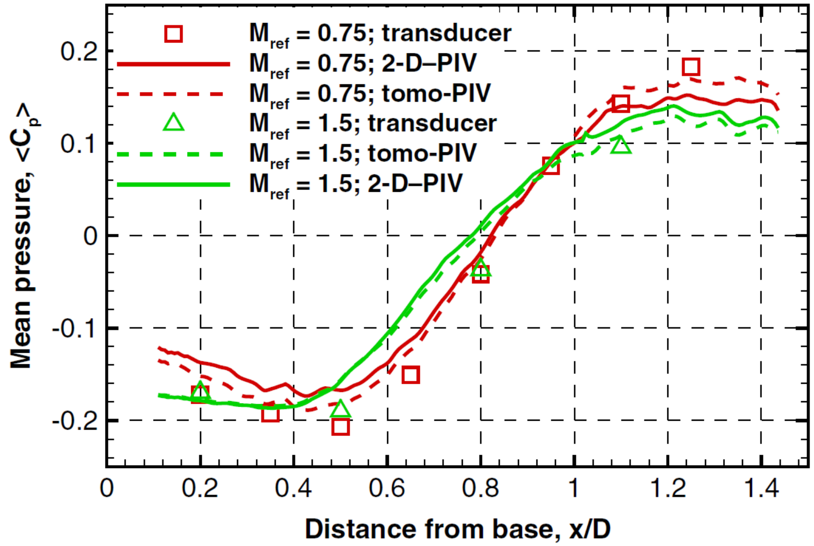


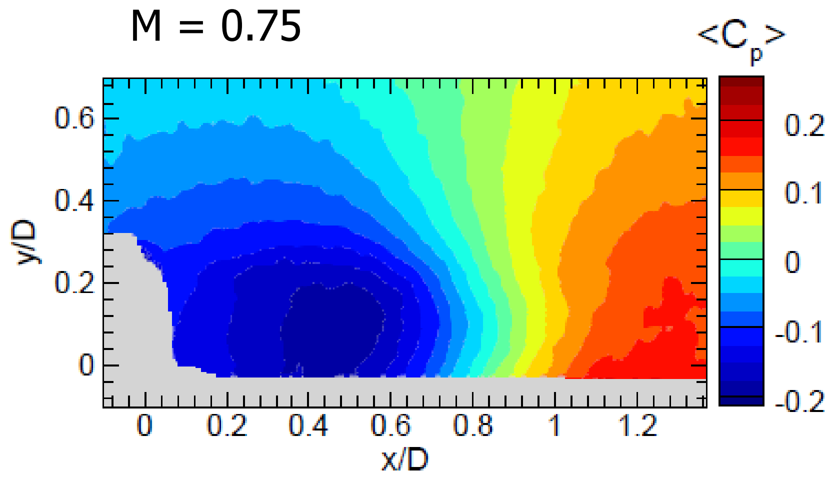
Mean pressure: compressible base flow experiments

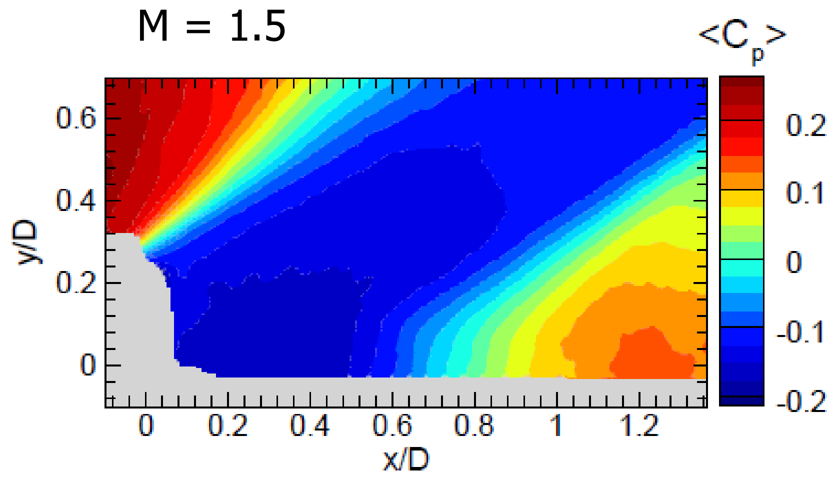
Pressure results

- Good agreement between PIV and transducer data, for transonic and supersonic flow
- Close agreement between 2D and tomo PIV data!

  -> planar PIV is "sufficient" in this case



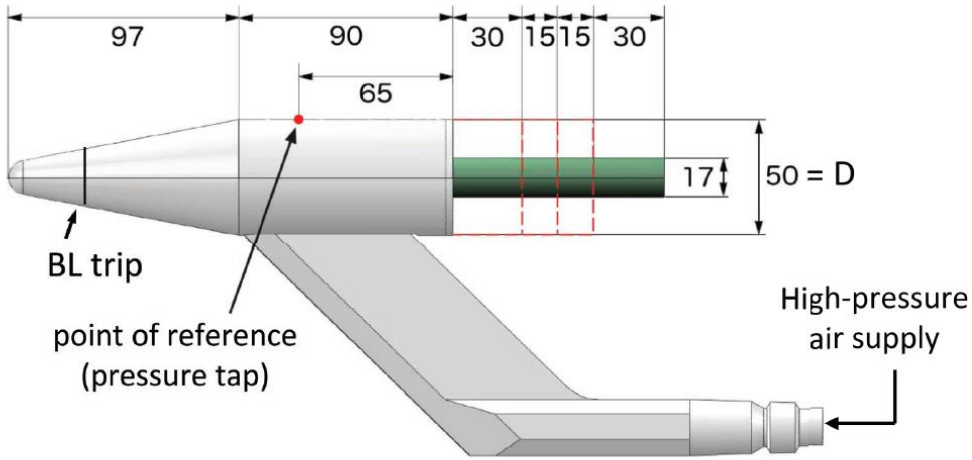




Base flow with simulated exhaust plume

Experimental set-up

- Side-sting-mounted model
- Effect of jet plume is simulated by compressed air supply
- Variable nozzle length (collars)
  L/D = 0.6, 0.9, 1.2, 1.8



Flow conditions

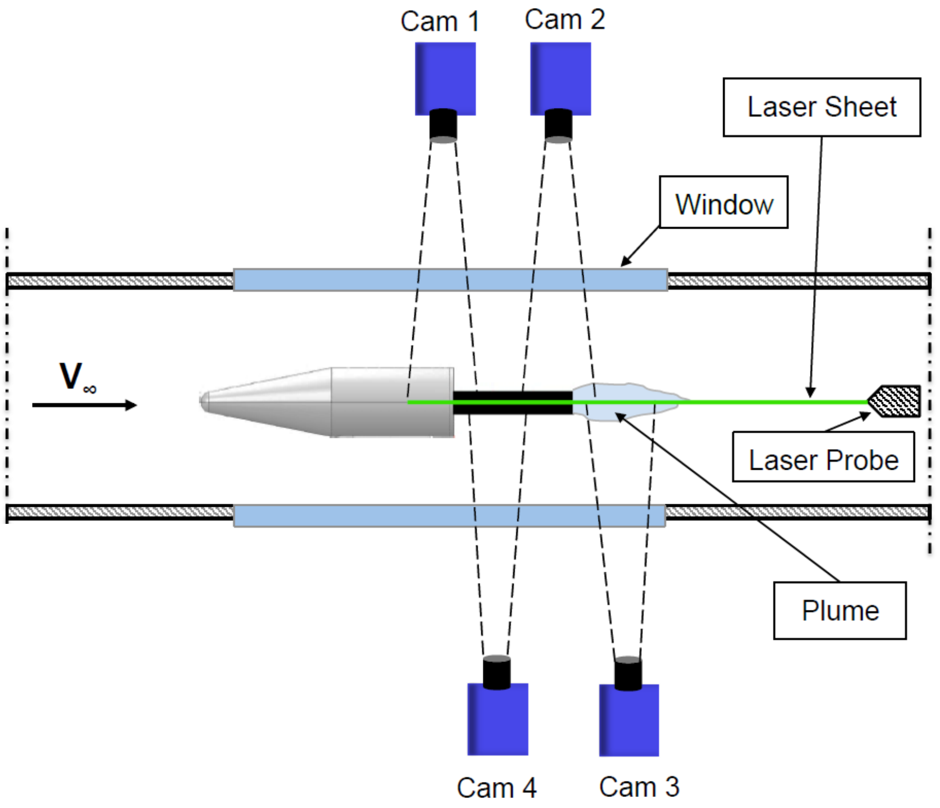
- Free-stream Mach number: M = 0.76 (transonic) and M = 2.2 (supersonic)
- Jet exit Mach number 3.5
- Jet (pressure) conditions are modelled after Ariane 5 Vulcain 2 operation
- In terms of jet pressure ratio: $\mathrm{JPR} = p_j/p_{amb}$
  - Transonic: $\mathrm{JPR} = 0.21$ (over-expanded)
  - Supersonic: $\mathrm{JPR} = 1.57$ (under-expanded)

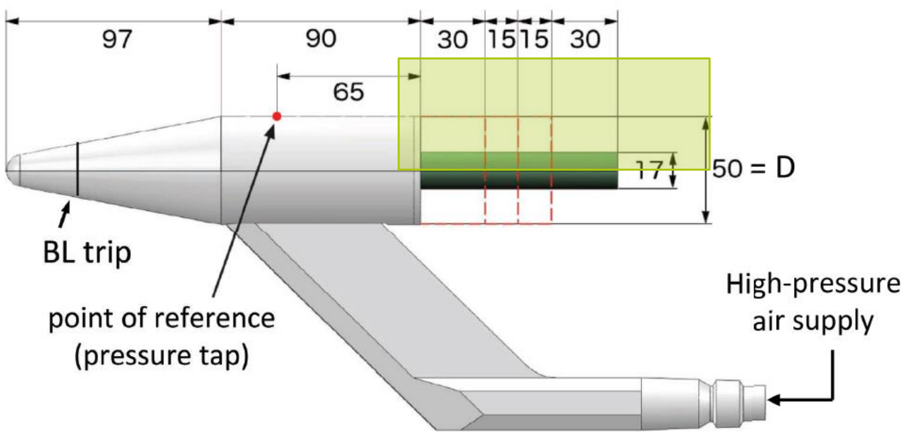
(Van Gent et al., AIAA Journal, 2019)

Base flow with simulated exhaust plume

PIV configuration

- Planar (2C) PIV
- Recording: 5 Hz in double-frame mode
- 4 cameras to extend field of view
- FOV size: 140 mm x 50 mm
- NB: only free stream flow is seeded





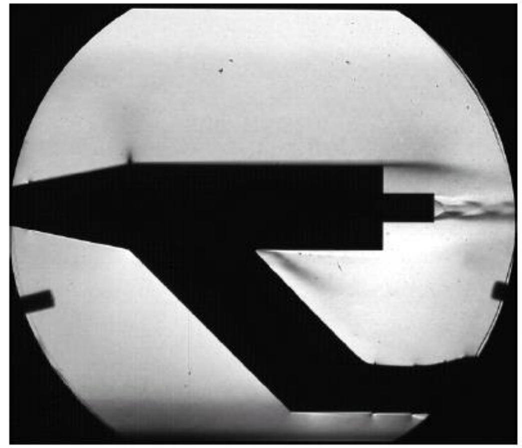
Base flow with simulated exhaust plume

Schlieren visualization

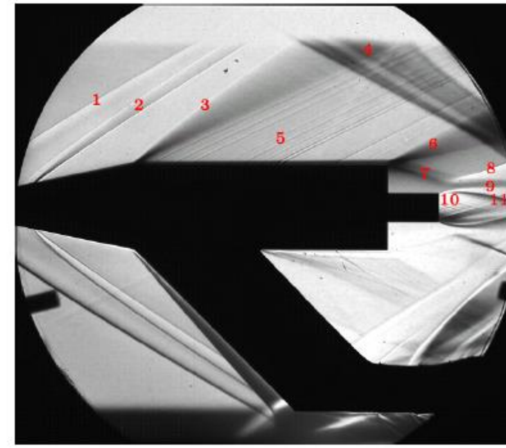
(with jet operative)

Shortest nozzle (L/D = 0.6)

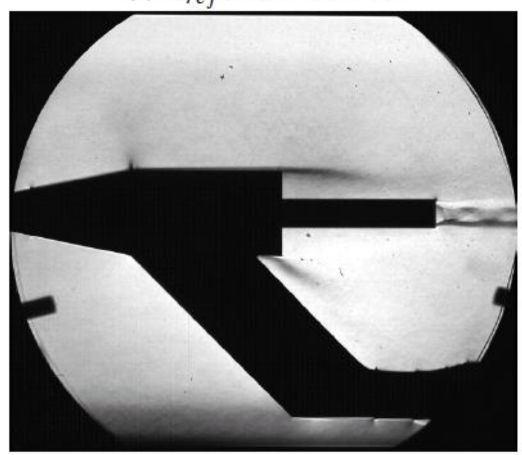
Longest nozzle (L/D = 1.8)



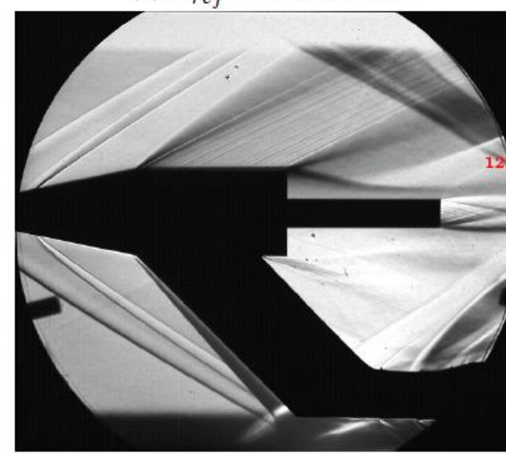
(a) $M_{ref} = 0.76; L/D = 0.6$



(b) $M_{ref} = 2.19; L/D = 0.6$



(c) $M_{ref} = 0.76; L/D = 1.8$



(d) $M_{ref} = 2.19; L/D = 1.8$

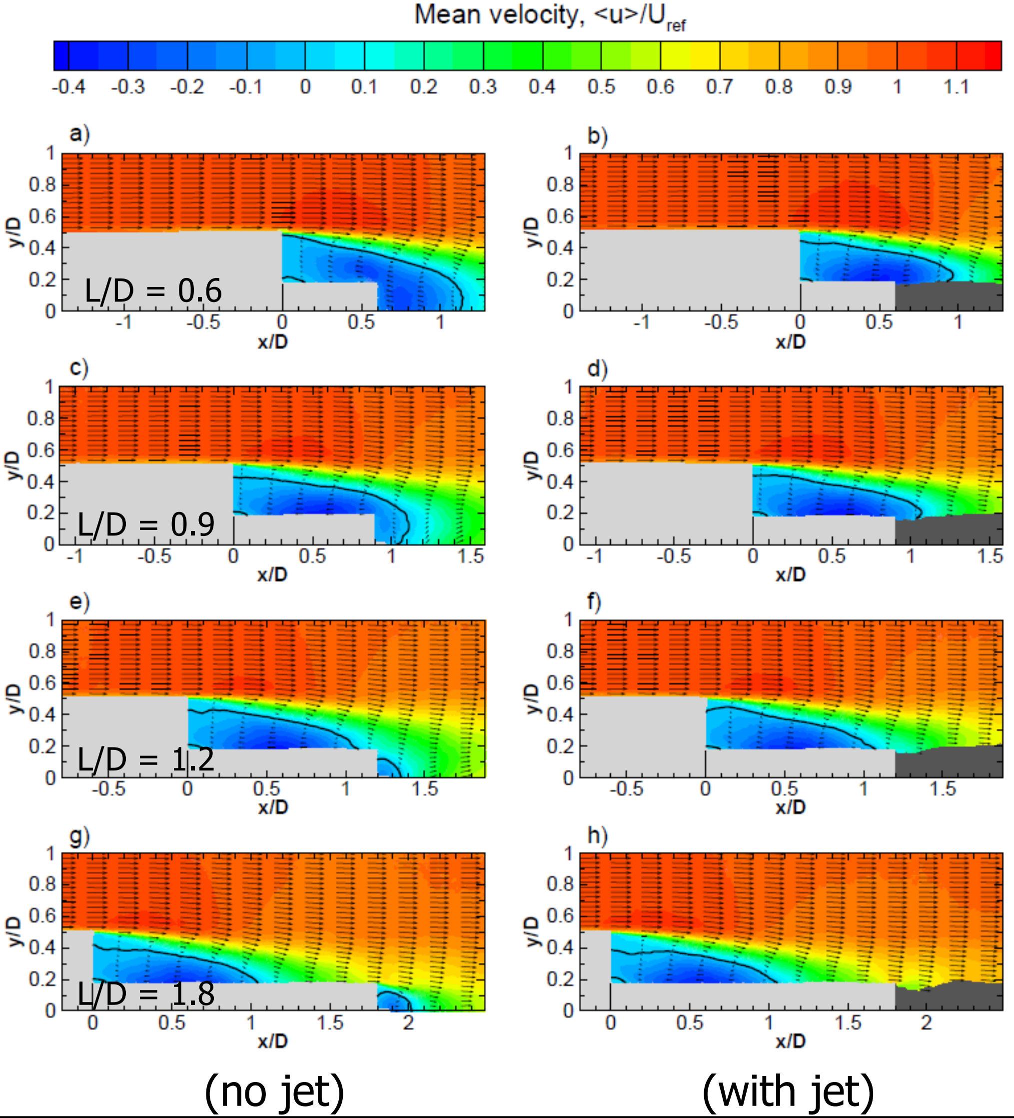
Transonic case M = 0.76
(over-expanded jet)

Supersonic case M = 2.19
(under-expanded jet)

Base flow with simulated exhaust plume

Transonic case

- Effect of nozzle length and jet on flow reattachment
- For L/D > 1.1 reattachment on after-body surface
- Flow unsteadiness reduces for longer afterbodies



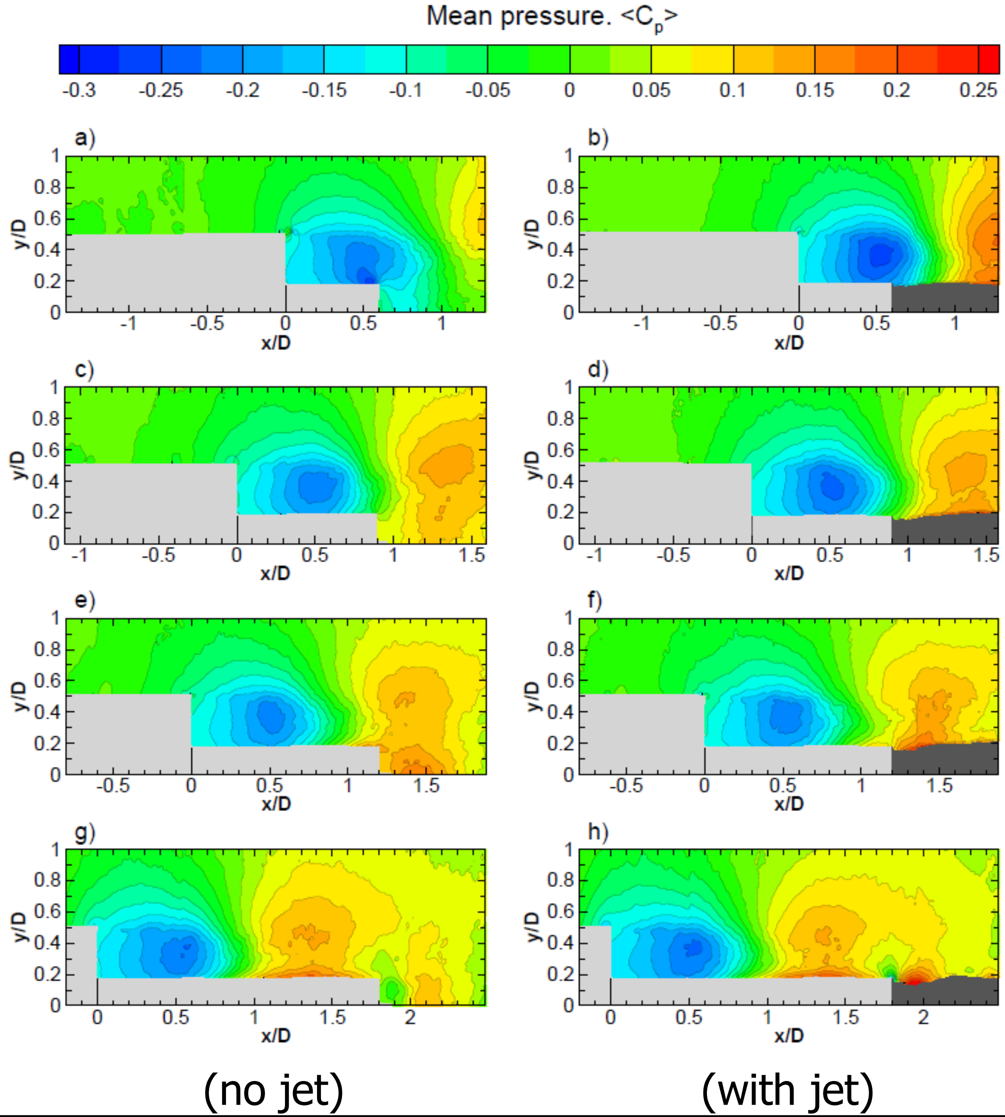
Base flow with simulated exhaust plume

Transonic case

- Effect of nozzle length and jet on flow reattachment
- For L/D > 1.1 reattachment on after-body surface
- Flow unsteadiness reduces for longer afterbodies

Pressure fields:

- Largest jet effect for the shortest nozzle



Conclusions

Operating principles

- Pressure (fluctuations) can be “measured” non-intrusively with PIV

Implementation:

- For (predominantly) 2D flows planar PIV is sufficient
- Volumetric data required for 3D flows
- Instantaneous pressure requires time information: time-resolved (low flow speed) or multi-pulse (high flow speed)
- Multi-pulse approach challenging due to system complexity and synchronization issues
- Mean pressure requires no time information (velocity data statistics only)

Applications:

- Transonic base flows (many others can be found in literature)