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ONERA

THE FRENCH AEROSPACE LAB

www.onera.fr

Facilities and metrologies of ONERA / DAAA: selected examples

Benjamin Leclaire, ONERA/DAAA, France

NWTF Conference, Birmingham

April 3rd, 2025

ONERA wind-tunnels

WT activities at ONERA:

- **Industrial**: « Wind-Tunnel division »
  - Large facilities, located in Modane, Le Fauga-Mauzac and Saclay (figure)

- **Research / semi-industrial**: scientific departements
  - Multi-Physics and Energetics (DMPE)
  - **Aerodynamics, Aeroelasticity, Acoustics (DAAA)**

Metrologies

WTs there as well!

https://www.onera.fr/en/windtunnel/testing-capabilities

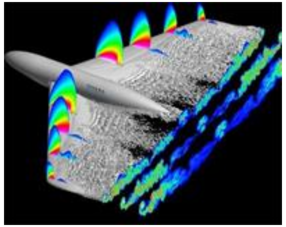
D epartment
A erodynamics
A eroelasticity
A coustics

Modeling

Simulation

Experimentation

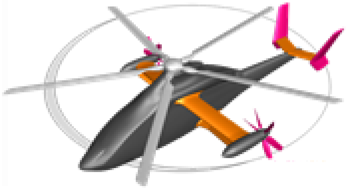
Advanced modeling Aerodynamics/Structure

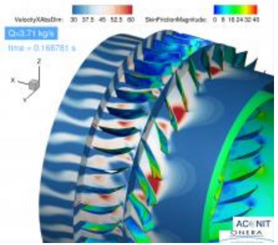


Novel configurations

Flow Control

Numerical Optimisation

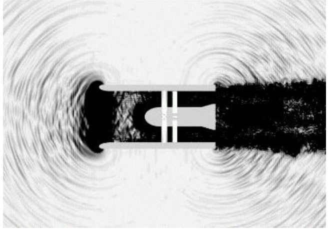




Software development

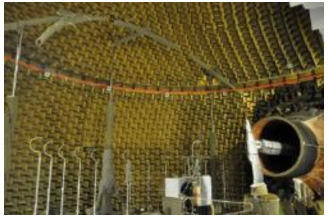
Experimental and Numerical Methods

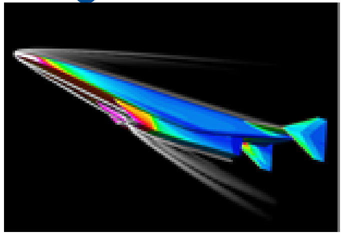
Performance prediction

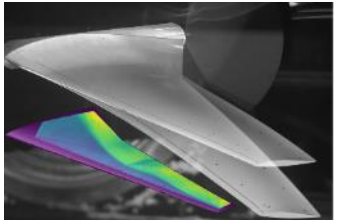


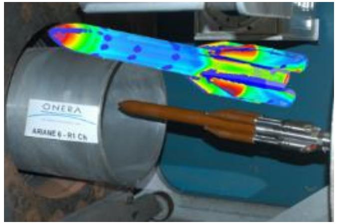
Complex physical phenomena

Flight dynamics at the boundaries of the flight domain









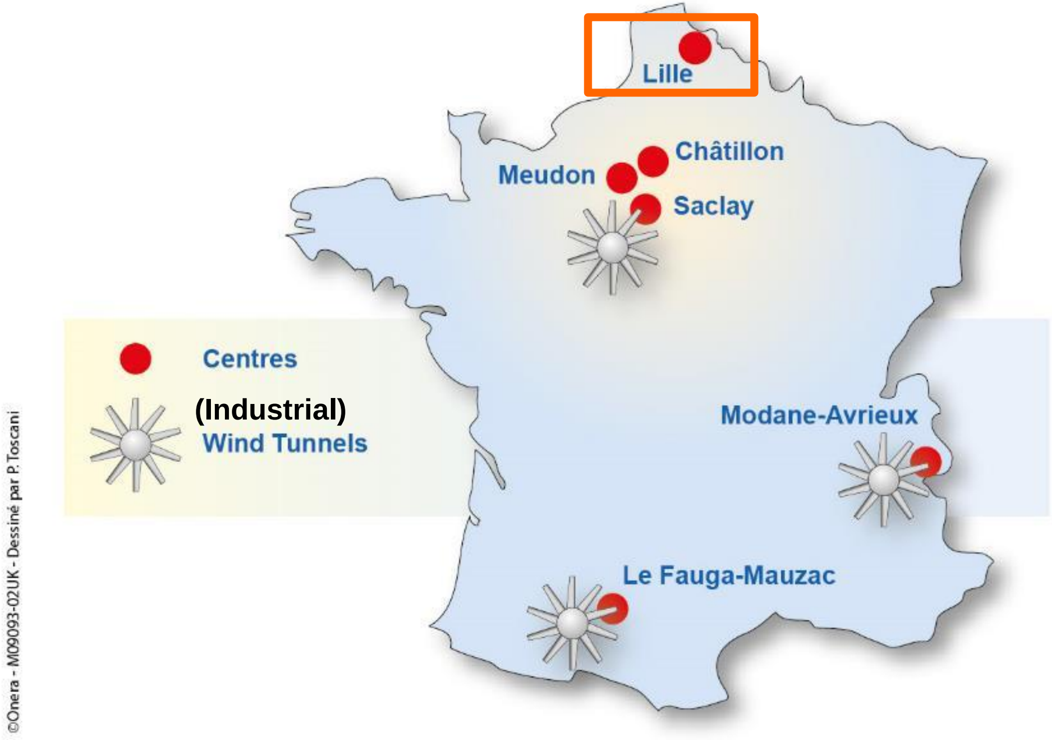
~ 220 permanent staff, ~ 60 PhDs students – 13 research units

Objective and outline

Present DAAA's main facilities and **metrological developments** through **selected** recent research projects:

- Focus on aerodynamics (+ a bit of aeroelasticity) – no acoustics
- Low-speed and high-speed
- Mix between semi-industrial and research type

DAAA Lille facilities



Facilities: overview – Lille

L1 wind tunnel
Section D2.4 m

Open or closed test section wind tunnel dedicated to research and industrial projects
From 0 to 75 m/s

L2 wind tunnel
Section 6x2.4 m^2

Non conventional aerodynamics (Drones, wind turbine, helideck…)
From 0 to 20 m/s

SV4 Wind Tunnel
Section D4m

Wind tunnel dedicated to stall and spin studies

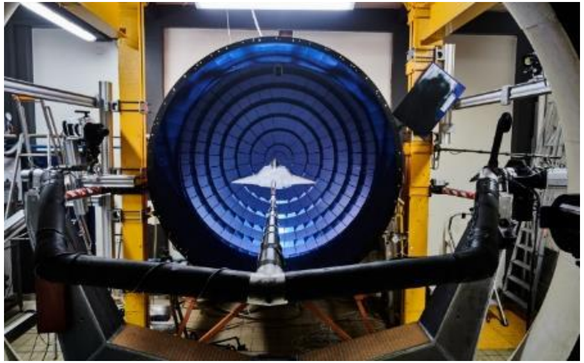
Flight laboratory B20

20m x 20m x 90m building
- ***Free flight studies***
- ***Gust wind tunnel***
- ***Drone investigations***

- **In total, 8 wind tunnels and 2 hydrodynamic installations**
- **Dedicated laboratory (optical metrology, free flight laboratory, Flow control…)**

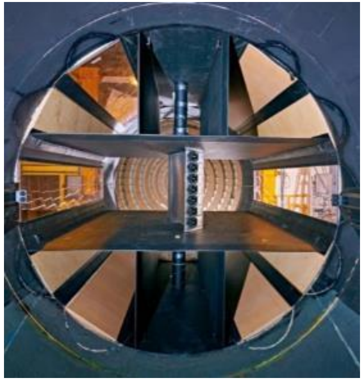
Lille L1 wind tunnel

Horizontal wind tunnel
- *Eiffel type with return circuit*
- *Circular test section $\phi = 2.4m$*
- *Velocity range from 0 to 75 m/s*
- *Open or closed test section*



Measurement capability
- *Aerodynamic forces and moments*
- *Static and total pressures*
- *Hot wire anemometry*
- *PIV and flow visualisation*
- *Object position tracking*

Model Supports
- *3-degree-of-freedom probing traverse system within the diffuser*
- *Motorized model support – PQR or “Swan Neck” dynamic measurements*



SUPERMAN project
SUPER MANoeuvrability

D. Farcy, G. Tanguy, N. Vauchel, G. Dubot, E. Garnier (2024), *Static and dynamic aerodynamic coefficients evaluation on a generic fighter configuration in ONERA low speed wind tunnels, AIAA2024-4066*

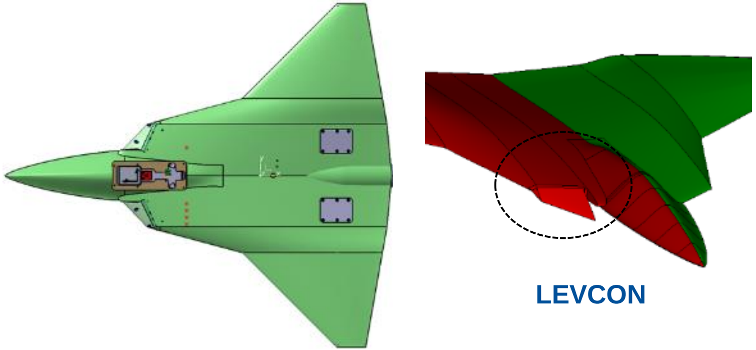
Characterisation of vortex breakdown on a 5th GEN. wing planform and flight dynamics identification for ROM model

- Generic wing planform ~1:25
- NATO ONERA-DLR collaboration
- Flight dynamics model identification
  - Dynamic test rig within two wind tunnels L1 and SV4
- Flow physics investigation at high angle of attack using S-PIV

LEVCONs (Leading-Edge Vortex CONtrol) motorisation

- Vortex breakdown control
- Integrated actuators
- Rotation Velocity up to 100° /s max
- From 0° to 30° deflection

SUPERMAN model on PQR (left) and rotary balance (right)



SUPERMAN project
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D. Farcy, G. Tanguy, N. Vauchel, G. Dubot, E. Garnier (2024), *Static and dynamic aerodynamic coefficients evaluation on a generic fighter configuration in ONERA low speed wind tunnels, AIAA2024-4066*

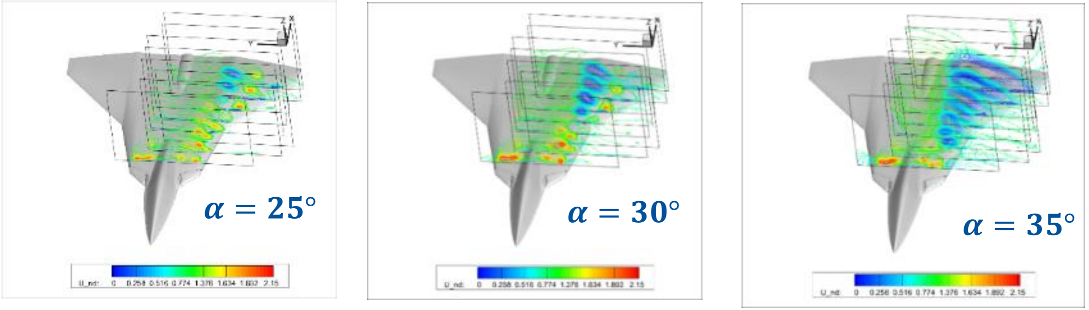
Stability, Control and Maneuverability

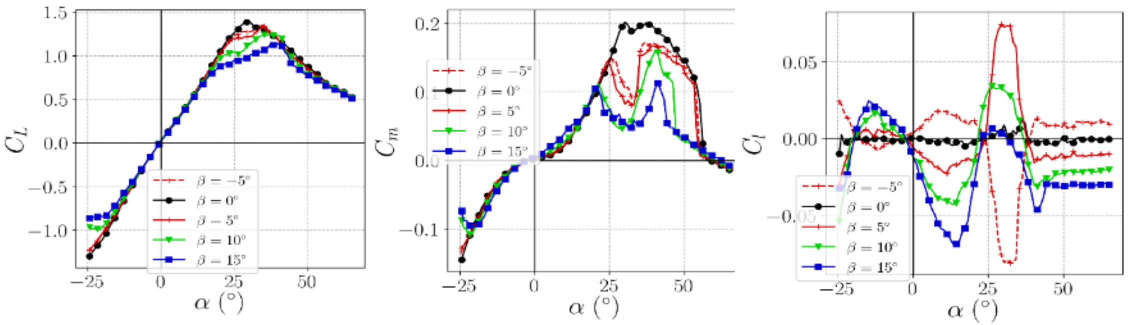
- Detailed flow characterization around vortex breakdown
- Force and moments measurements for high range of incidence and side slip angle

Identification of 4 regions :

- Region 1: $\alpha \in [0,7°]$: dominant potential flow
- Region 2: $\alpha \in [7°, 12°]$: Intensification of vortical flow
- Region 3 : $\alpha \in [12°, 30°]$: Vortex breakdown on the windward wing: appears and moves upstream. Intensification on the leeward wing
- Region 4 **:** $\alpha \approx 30°$, vortex breakdown at the leeward wing and stall

PIV longitudinal velocity fields for $U_\infty = 35\, m.s^{-1}$





Static forces and moments measurements

SUPERMAN project
SUPER MANoeuvrability

* Isnard B., Tanguy G., Farcy D., Garnier E, Foucaut JM, (2024). Identification method of longitudinal coefficients based on the numerical study of the flow topology around the SACCON geometry, ICAS 2024

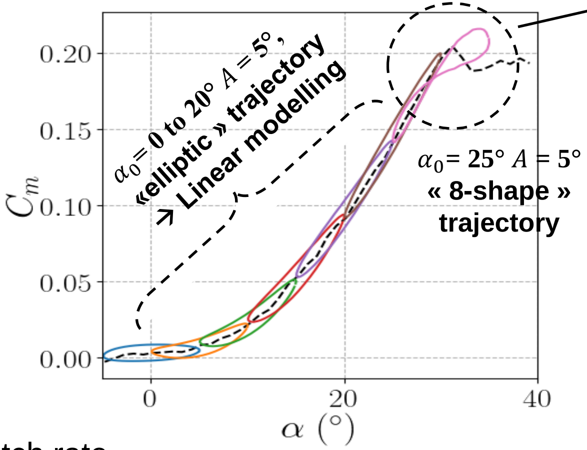
Identification of ROM – Dynamic effects

$$\boldsymbol{C_i}(\alpha, q, \dot{\alpha}, \dot{q}) = C_{i0}(\alpha_0) + \overline{C_{i\alpha}}\, A\cos(2\pi f t) - \overline{C_{iq^*}}\, 2\pi f A \frac{c}{V} \sin(2\pi f t)$$

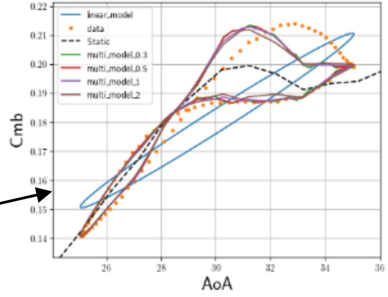
Static term | **In-phase term (slope)** | **Out-of-phase term (thickness)**

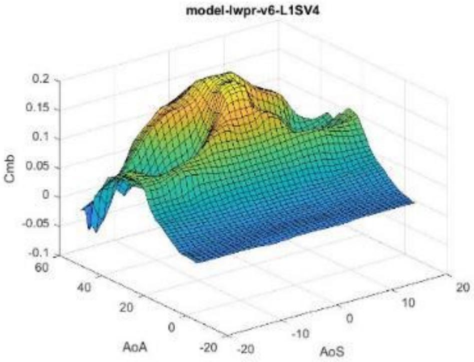
Forced oscillations tests at L1

- ➢ Dynamic derivatives relative to pitch rate
- ➢ Effect of amplitude / frequency



Multi-point identification method for non linear variations *



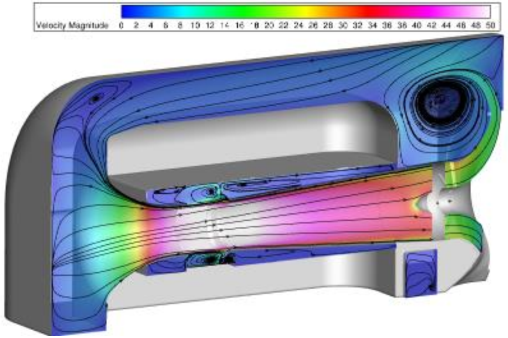


Superman model development (pitching moment)

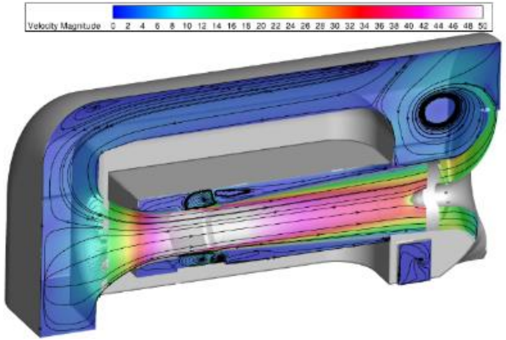
SIMEX project

SIMulation of EXperimental facilities – ONERA elsA solver, unstructured mesh

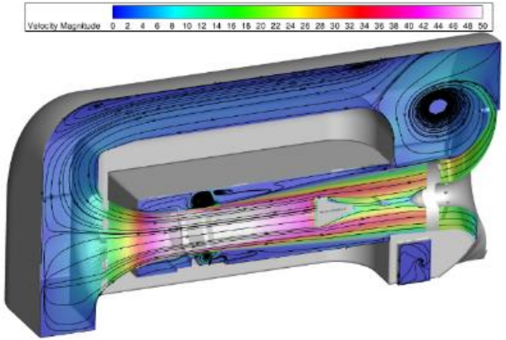
Reference (94M cells)

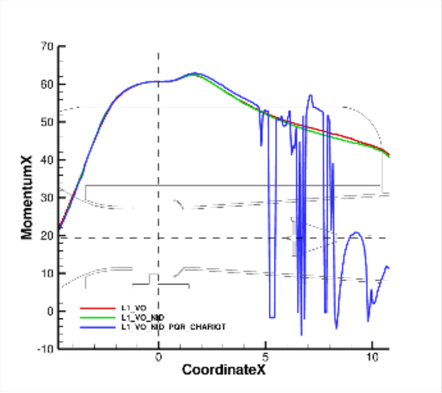


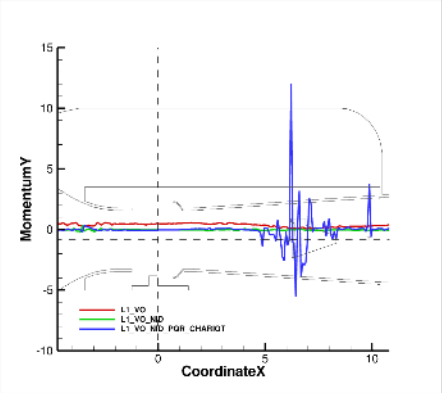
Ref. + honeycomb (283M cells)

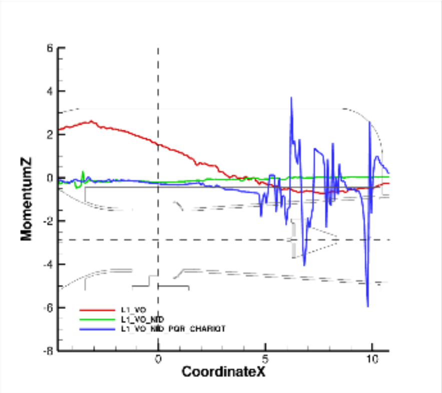


Ref. + HC + PQR + probing (322M cells)

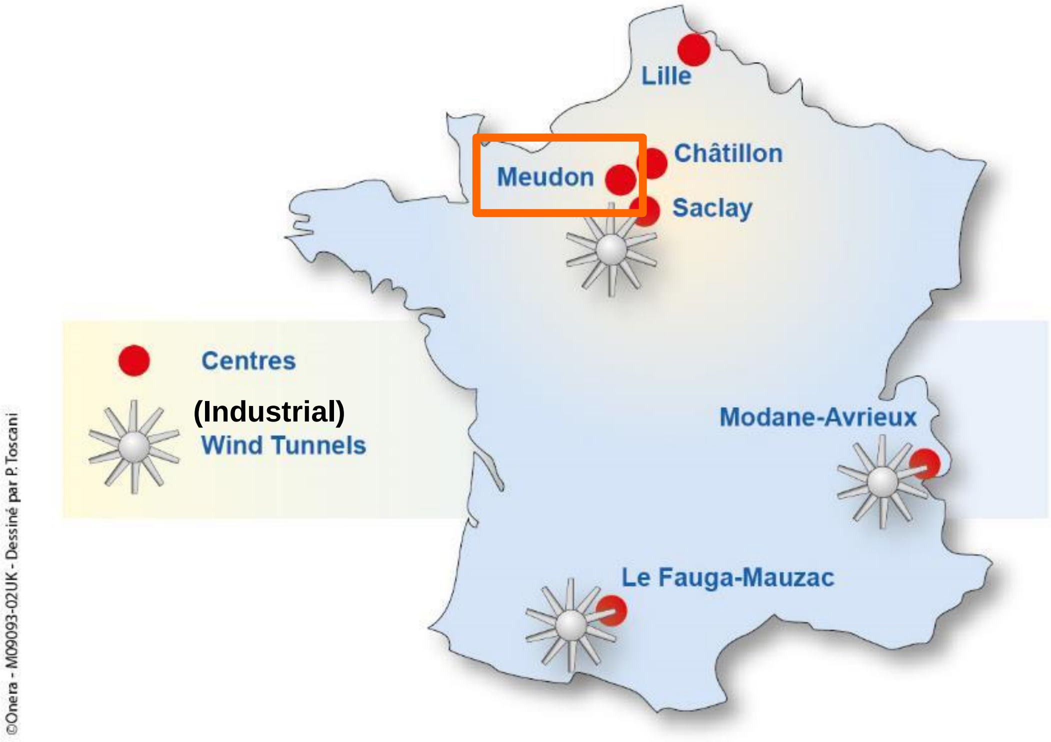




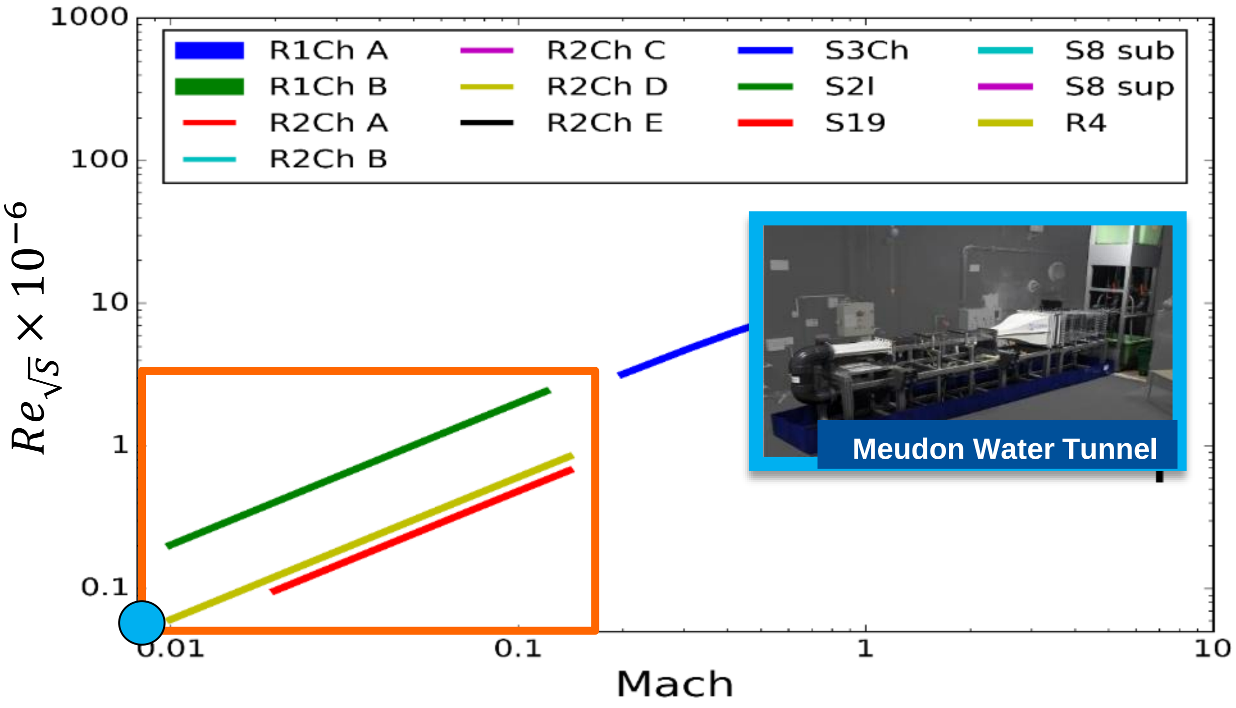




DAAA Meudon facilities



Facilities: overview – Meudon

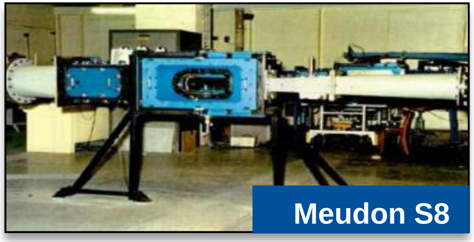


Facilities: overview – Meudon

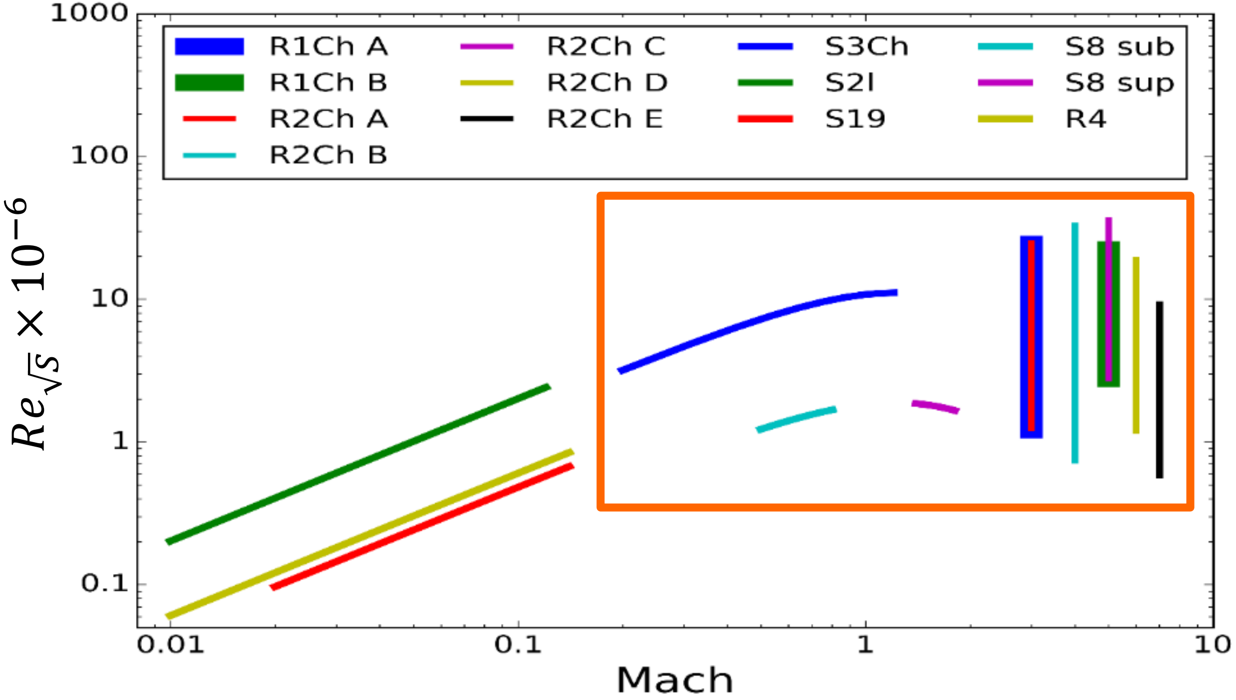
Meudon R1Ch & R2Ch

$$Re = \frac{\rho U S^{1/2}}{\mu}$$

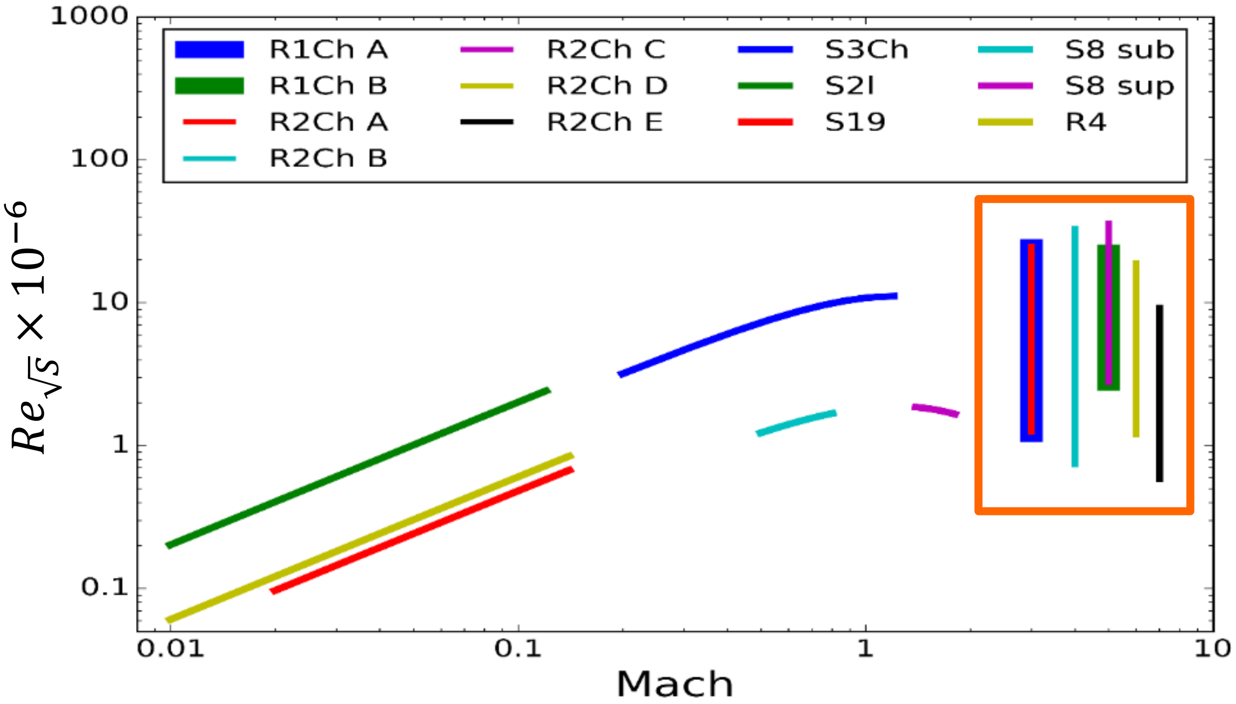
Meudon S3Ch



Meudon S8



Facilities: overview – Meudon



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Meudon blow-down WTs: R1 & R2Ch

R1Ch

- Mach 3 nozzle, exit diameter D = 0,311m
- Mach 5 nozzle, exit diameter D = 0,327m
- Stagnation pressure: 1 to 15 bar
- Stagnation temperature < 400K
- Max flow rate 80 kg/s
- Reynolds (/meter) 4M to 125M

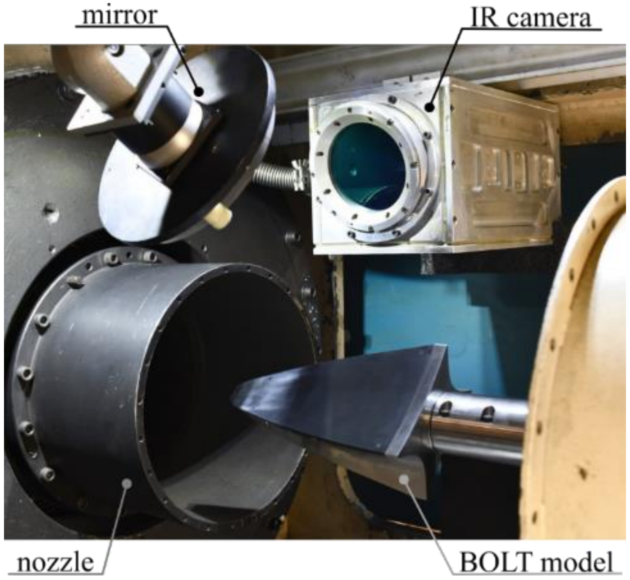
R2Ch

- Mach 3/4 nozzles, exit diameter D = 0,190m
- Mach 5/6/7 nozzles, exit diameter D = 0,327m
- Stagnation pressure: 1 to 70 bar
- Stagnation temperature < 750K
- Max flow rate 40 kg/s
- Reynolds (/meter) 1M to 40M

BOLT forebody tests

Experimental setup

L. Sombaert, F. Nicolas, M. Lugrin, N. Severac, S. Esquieu, R. Bur, *Hypersonic boundary-layer transition on the BOLT forebody in the R2Ch facility*, Exp. Fluids, in revision

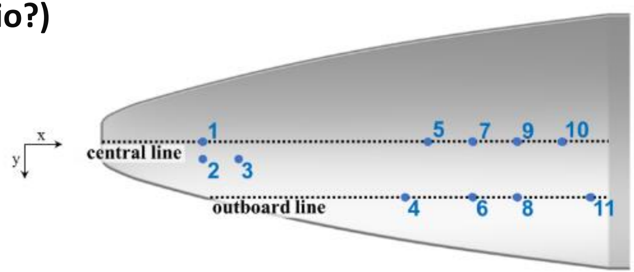


- Experimental setup @R2Ch, incl. IR thermography

- **Operating conditions:**

  Mach 6 ($Re_{max} = 50 \times 10^6$ **m**$^{-1}$) **and 7** ($Re_{max} = 30 \times 10^6$ **m**$^{-1}$)

- **Explore the boundary layer transition physical process, esp. at Mach 7 (specific transition scenario?)**

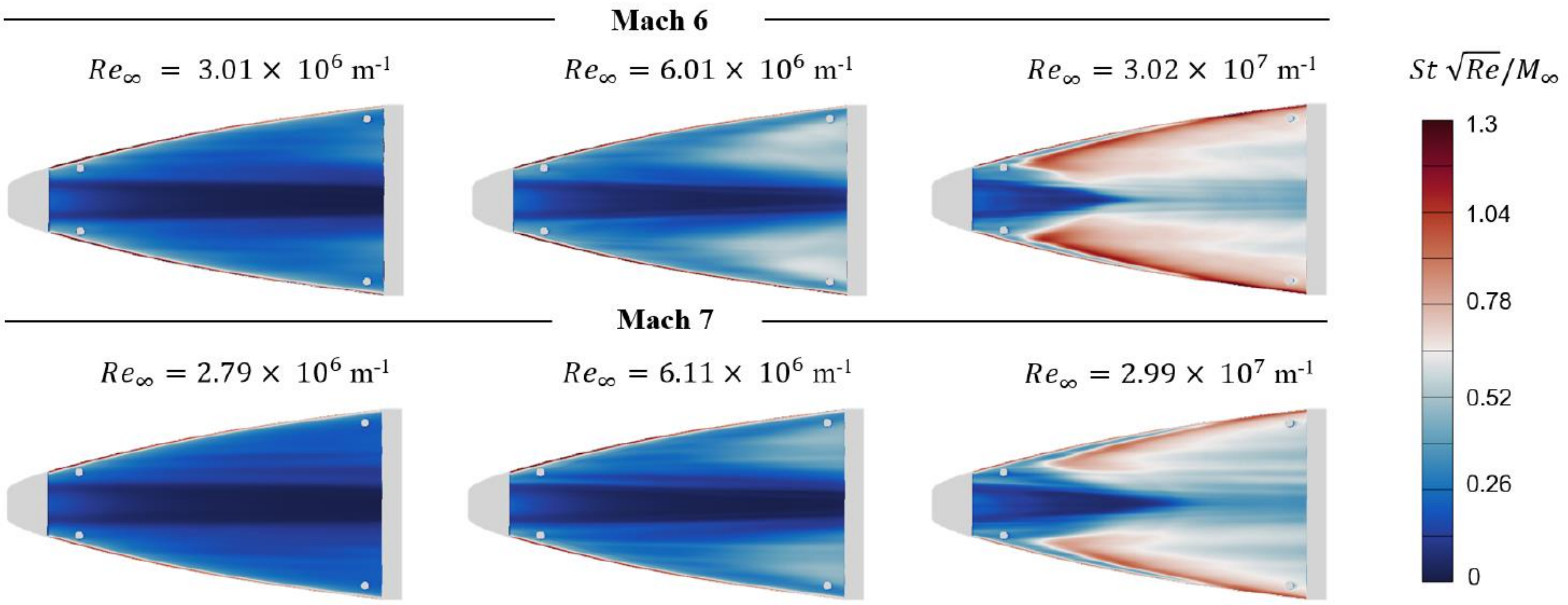


- **Model at 1/3 scale of flight geometry (288.67 mm long)**
- **PEEK surface for infrared thermography**
- **11 PCB 132-B38 unsteady pressure sensors (~300 kHz)**
- **Specific care during design to minimise surface roughness**

BOLT forebody tests

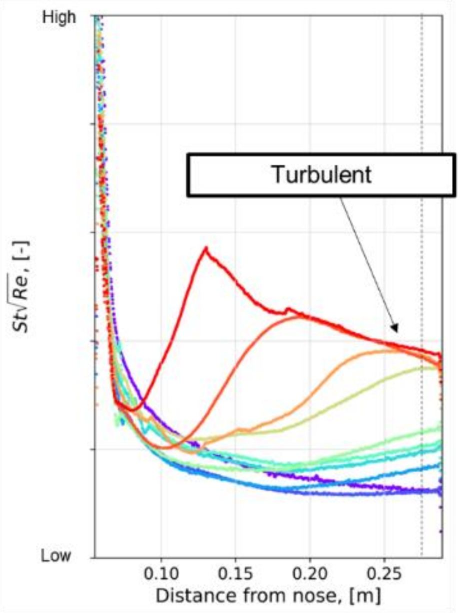
Heat flux maps

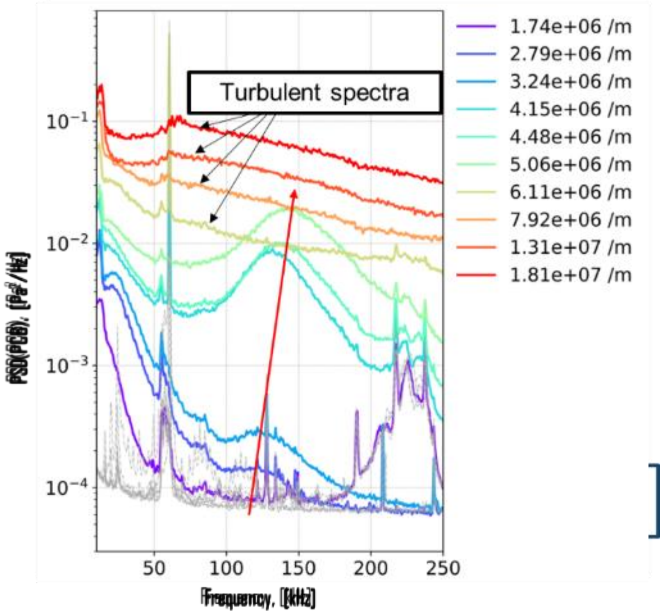
L. Sombaert, F. Nicolas, M. Lugrin, N. Severac, S. Esquieu, R. Bur, *Hypersonic boundary-layer transition on the BOLT forebody in the R2Ch facility*, Exp. Fluids, in revision



BOLT forebody tests
Correlating heat flux and wall pressure

L. Sombaert, F. Nicolas, M. Lugrin, N. Severac, S. Esquieu, R. Bur, *Hypersonic boundary-layer transition on the BOLT forebody in the R2Ch facility*, Exp. Fluids, in revision





Hypersonic BL transition: CCF12

E. K. Benitez, C. Caillaud, Z. A. McDaniel, M. Lugrin, S. Esquieu, M. P. Borg, J. S. Jewell, A. Scholten, P. Paredes, F. Li, M. M. Choudhari, *Separation and transition on a cone-cylinder-flare: experimental campaigns*, AIAA SciTech Forum, 2024

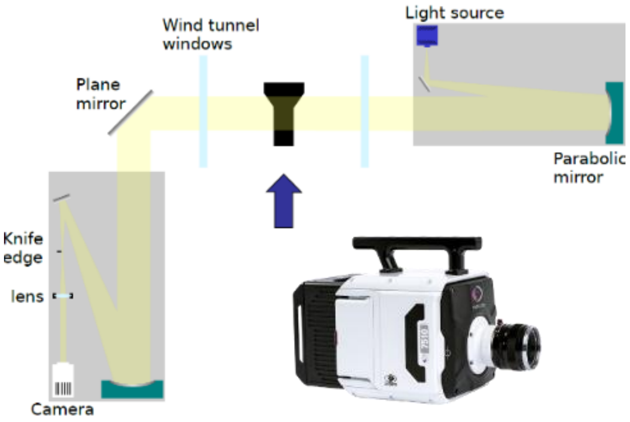
ONERA/CEA joint test campaign at R2Ch on Cone-Cylinder-Flare (CCF) with 12° flare angle (CCF12):

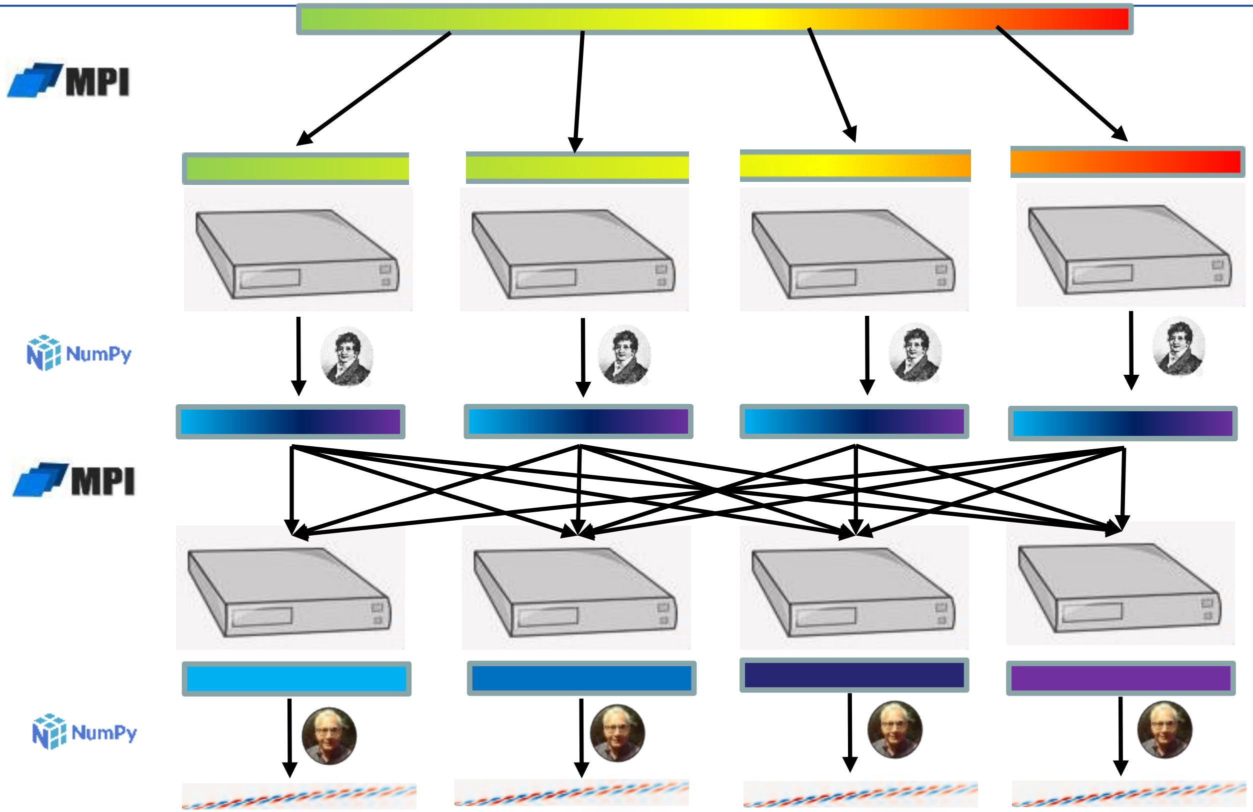
- Investigation (pressure sensors + Schlieren imaging) of unstable modes responsible for transition
- CFD / experiment comparison
- Validation of CEA's embarked measurement systems

Hypersonic BL transition: CCF12

Distributed Spectral POD

E. K. Benitez, C. Caillaud, Z. A. McDaniel, M. Lugrin, S. Esquieu, M. P. Borg, J. S. Jewell, A. Scholten, P. Paredes, F. Li, M. M. Choudhari, *Separation and transition on a cone-cylinder-flare: experimental campaigns*, AIAA SciTech Forum, 2024



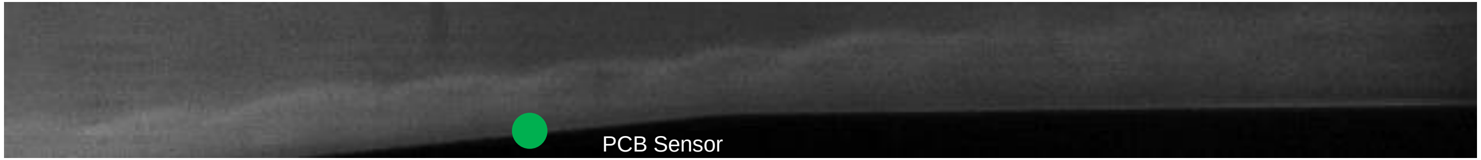


- TMX7510 (CEA)
  - 1.7MHz
  - 100ns exposure
  - 128Go acquired per run

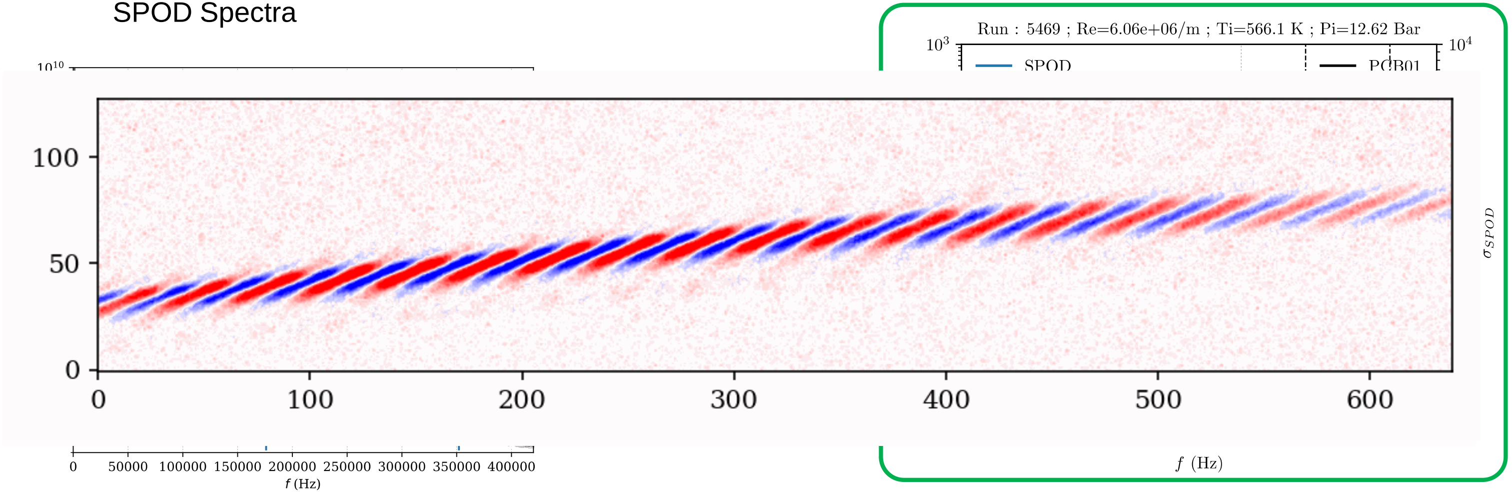
Hypersonic BL transition: CCF12

SPOD modes vs wall pressure

E. K. Benitez, C. Caillaud, Z. A. McDaniel, M. Lugrin, S. Esquieu, M. P. Borg, J. S. Jewell, A. Scholten, P. Paredes, F. Li, M. M. Choudhari, *Separation and transition on a cone-cylinder-flare: experimental campaigns*, AIAA SciTech Forum, 2024



SPOD Spectra



Hypersonic BL transition: CCF12

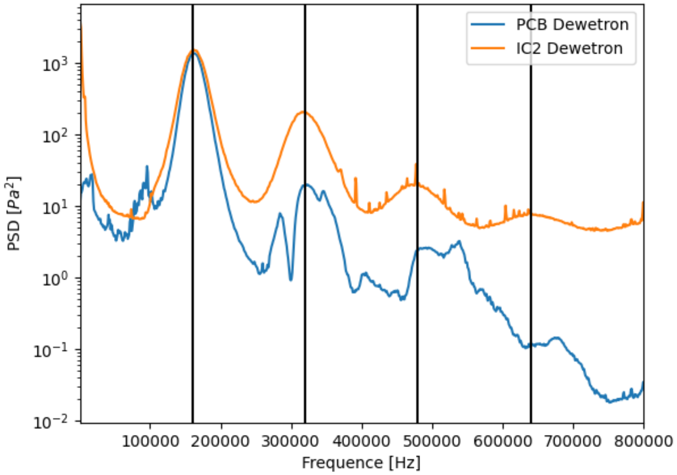
Next choice of sensors

➲ **PCB 132**

$\sim 10 \rightarrow 500$ kHz

➲ **IC2 MHz**

$\sim 0.1 \rightarrow 1000$ kHz



Facilities: overview – Meudon

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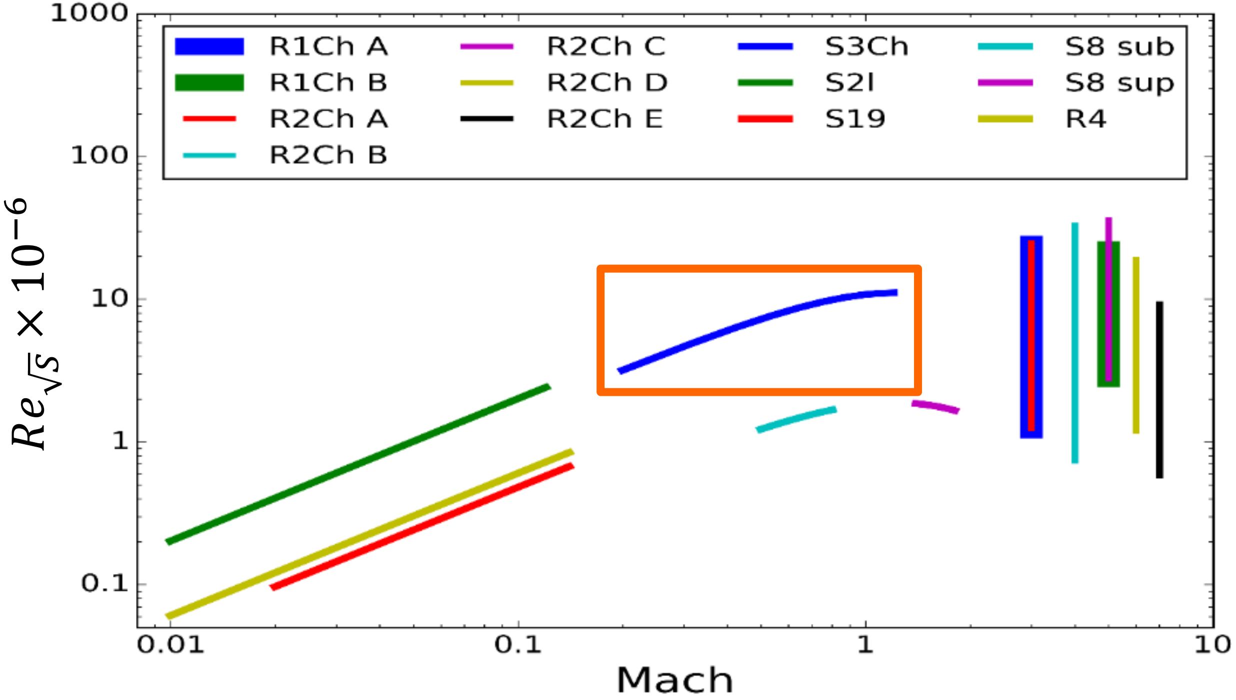


Meudon large transonic WT: S3Ch

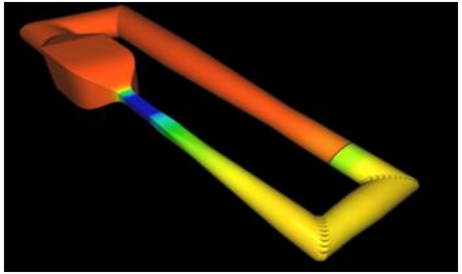
Continuous, closed-circuit atmospheric WT

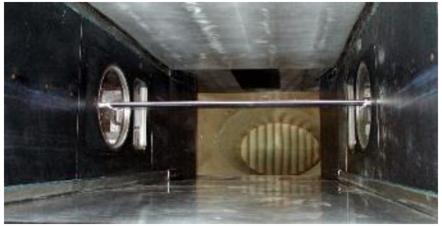
Mach from 0,1 to 1,3, stabilized through second throat

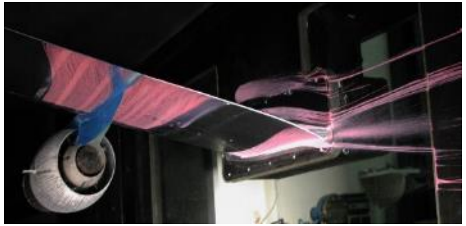
Test section: 804mm (width) x 764mm (height) x 2200mm (length), lower and upper deformable walls to minimize interference

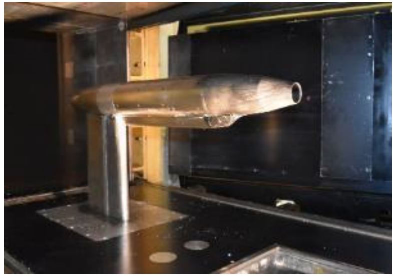
Heat exchanger enabling stabilized temperature in the 300 - 320K range

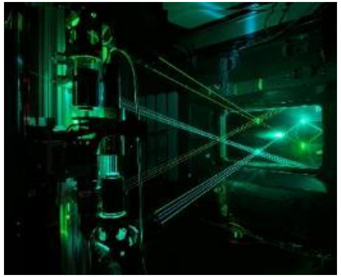
Lateral optical accesses (+ on upper and lower non-deformable walls)

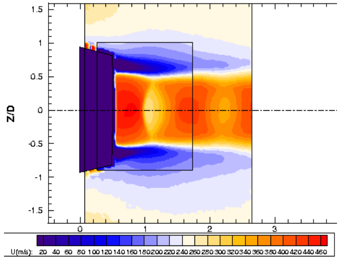








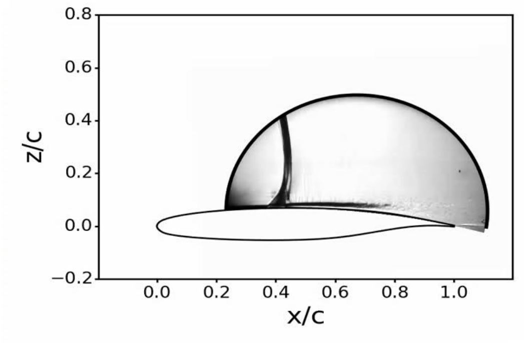




Transonic buffet aeroelastic lock-in

L. Sicard, C. Thémiot, V. Brion, *Experimental characterization of the transonic buffet lock-in phenomenon for an airfoil in free pitching and pluging motion*, AERO 25: 58th 3AF Int. Conf. on Appl. Aero., 2025

TRANSONIC BUFFET

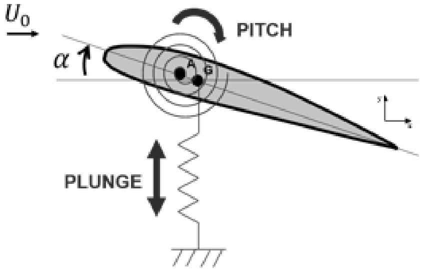


UE Buterfli project, Brion 2016

- Aerodynamic instability
- Periodic shock wave oscillations
- Threshold in Mach number and angle of attack

+

OSCILLATING STRUCTURE



- Forced/Free oscillation
- Specific natural frequency and oscillation amplitude

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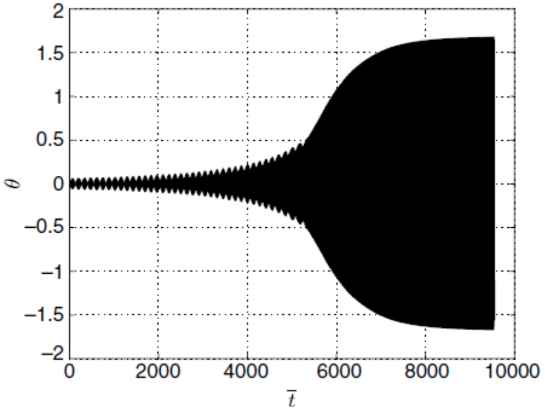
LOCKIN PHENOMENON

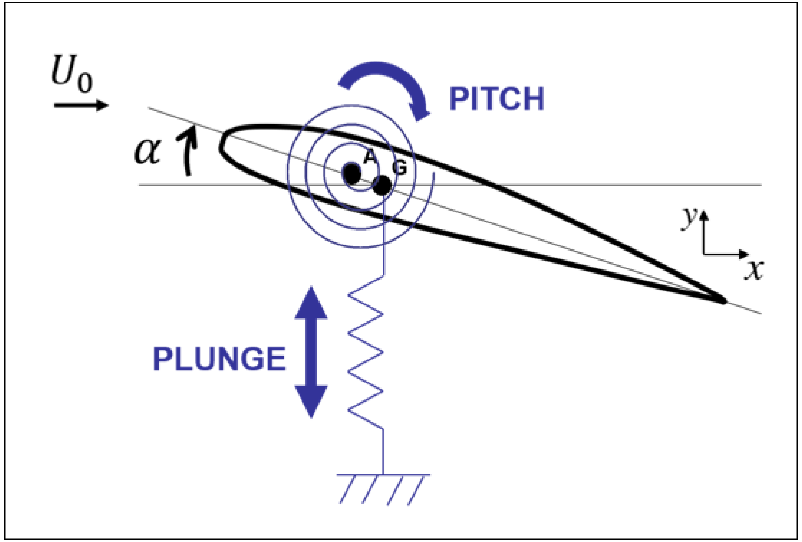


Raveh, D. E., & Dowell, E. H., 2014, AIAA journal, 52(5), 926-934.

Transonic buffet aeroelastic lock-in

Model and mesurements

L. Sicard, C. Thémiot, V. Brion, *Experimental characterization of the transonic buffet lock-in phenomenon for an airfoil in free pitching and pluging motion*, AERO 25: 58th 3AF Int. Conf. on Appl. Aero., 2025



- OAT15A AIRFOIL (Jacquin et al. 2009)
  c = 0.25 m ➔ buffet ~ 70Hz (St ~ 0.07)
  S = 0.8 m
  Tripping by catcut 89/102 µm for x/c = 7%

- FLOW PARAMETERS
  Plunge/Pitch frequency
  Mach : [0.3 : 0.8]
  Reynolds (chord based) : [1.5 : 3] 10^6
  Angle of attack : [0 : 4.5]°
  Degrees of freedom : None / Pitch or Plunge only / Pitch and Plunge

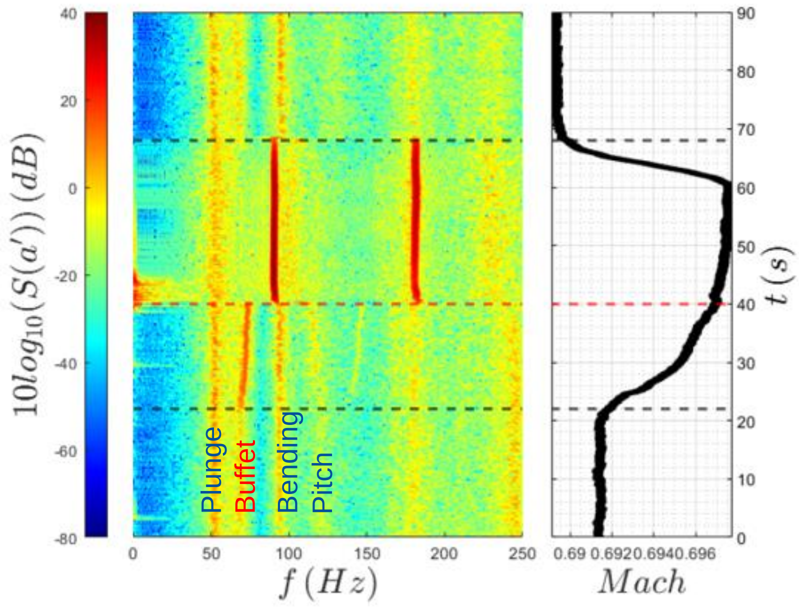
- MEASUREMENTS
  Pressure taps and Kulite, accelerometers, Keyence optical sensors, High-Speed SPIV

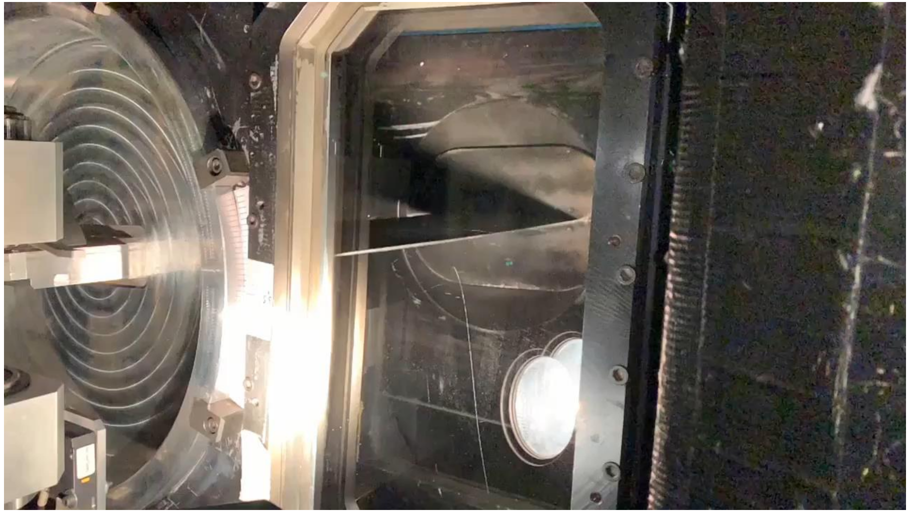
Transonic buffet aeroelastic lock-in

Structural dynamics

L. Sicard, C. Thémiot, V. Brion, *Experimental characterization of the transonic buffet lock-in phenomenon for an airfoil in free pitching and pluging motion*, AERO 25: 58th 3AF Int. Conf. on Appl. Aero., 2025

AoA = 3.5°
Pitch ~ 120 Hz & Plunge ~ 50Hz
Bending ~ 90 Hz





Transonic buffet aeroelastic lock-in

Fluid dynamics

L. Sicard, C. Thémiot, V. Brion, *Experimental characterization of the transonic buffet lock-in phenomenon for an airfoil in free pitching and pluging motion*, AERO 25: 58th 3AF Int. Conf. on Appl. Aero., 2025

AoA = 3.5°
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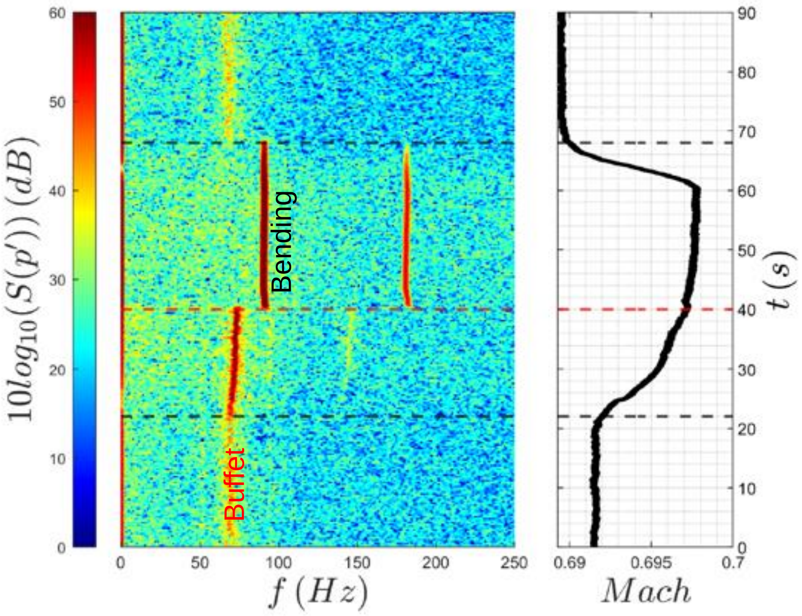
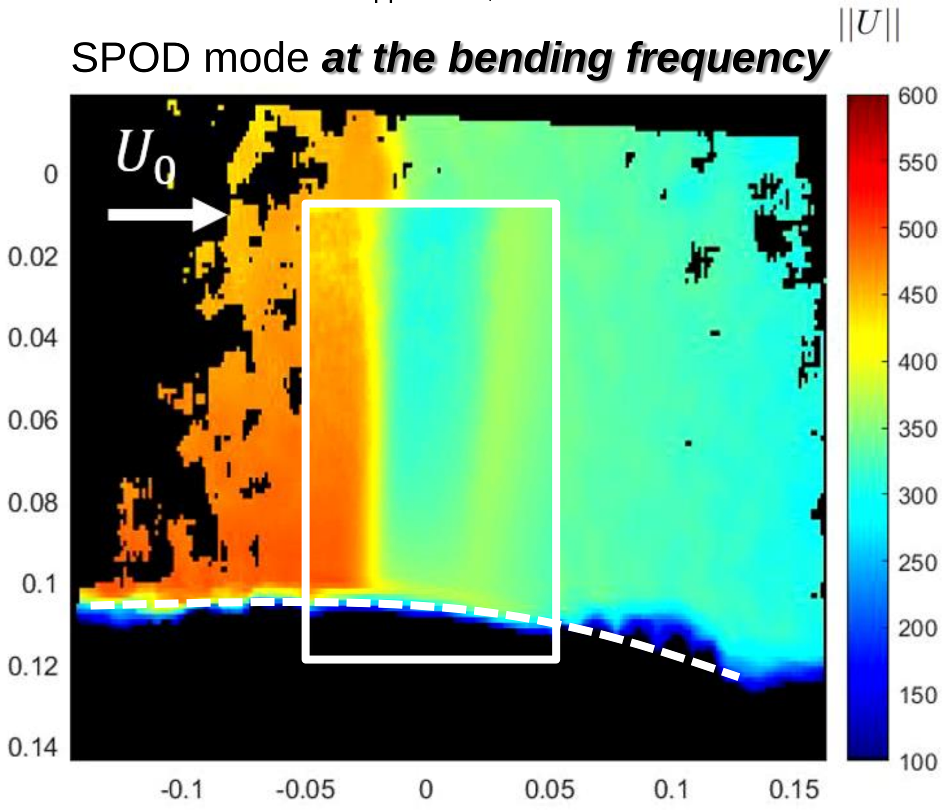
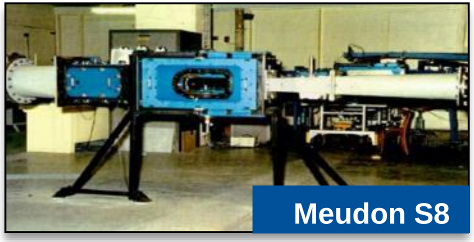
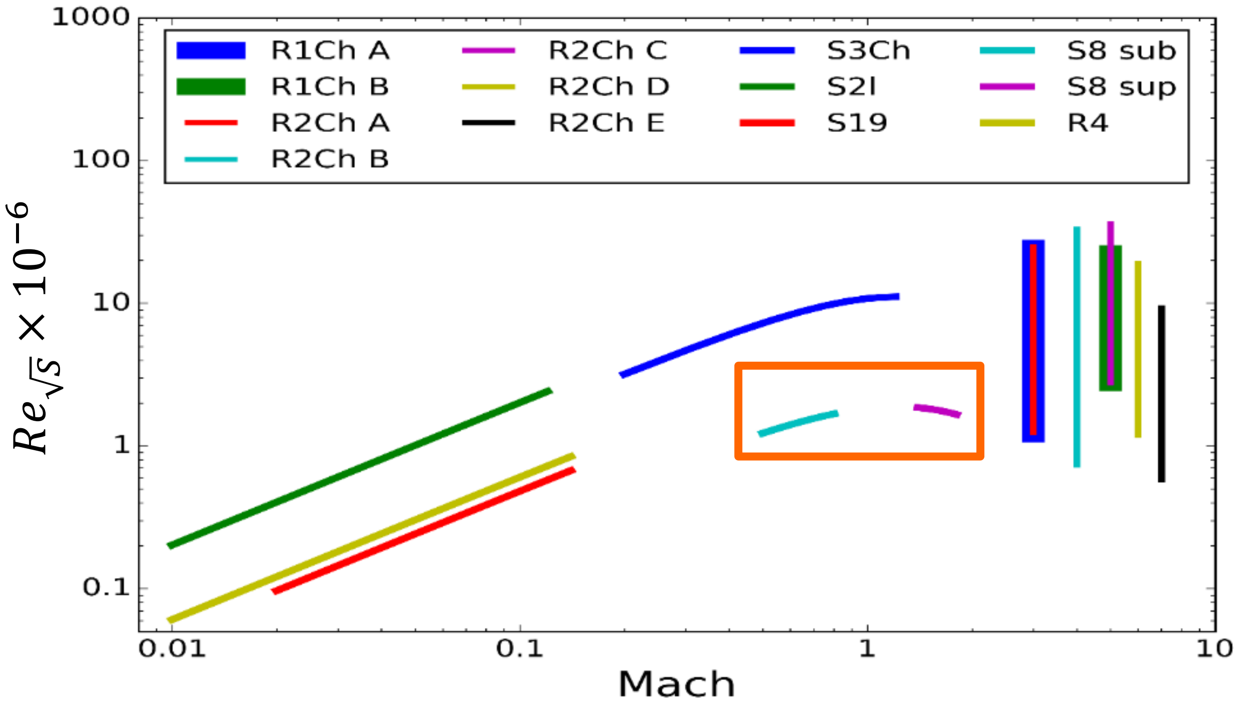


SPOD mode ***at the bending frequency***



Facilities: overview – Meudon





Temperature corrected unsteady PSP

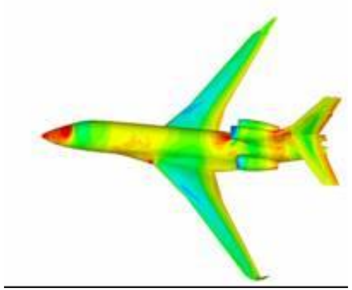
O. Le Bourgeois, F. Nicolas, M. Couliou, B. Fond, *A temperature-corrected Ruthenium and inorganic phosphor-based fast responding pressure sensitive paint*, AIAA SciTech Forum, 2025.

→ Pressure Sensitive Paints (PSPs)

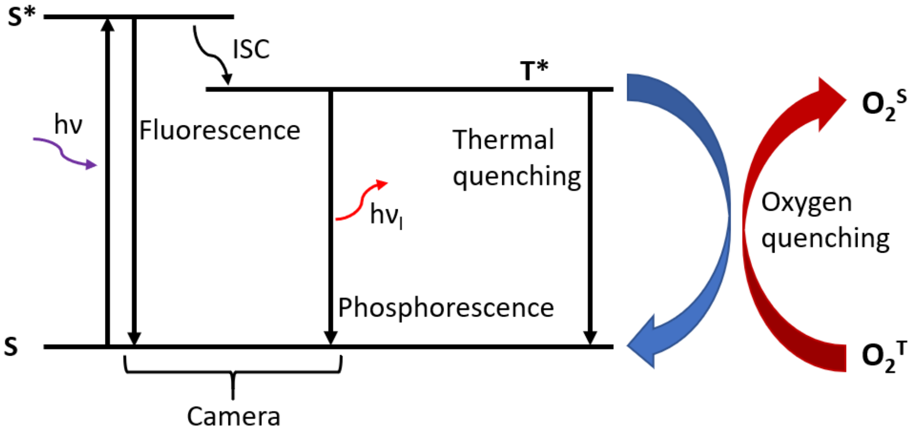
- → Luminescent emission depending on the air pressure at the model surface
- → Global pressure distribution over the model

(a)

(b)



Falcon 7X Model (a) and the measured pressure field (b), ONERA



Increase in pressure:

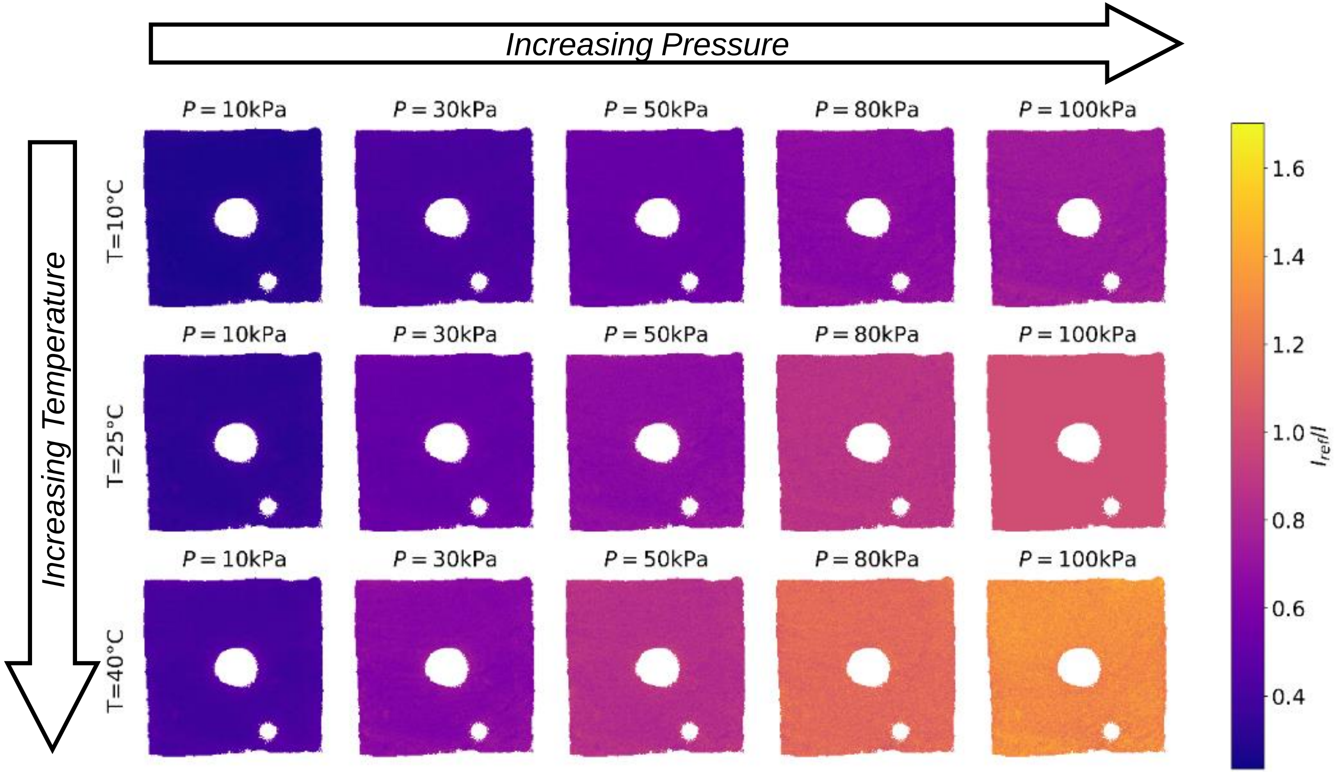
→ Increase in O_2^T concentration

→ Increase in oxygen quenching

→ <u>The luminescence intensity is inversely proportional to the air pressure</u>

Temperature corrected unsteady PSP

O. Le Bourgeois, F. Nicolas, M. Couliou, B. Fond, *A temperature-corrected Ruthenium and inorganic phosphor-based fast responding pressure sensitive paint*, AIAA SciTech Forum, 2025.

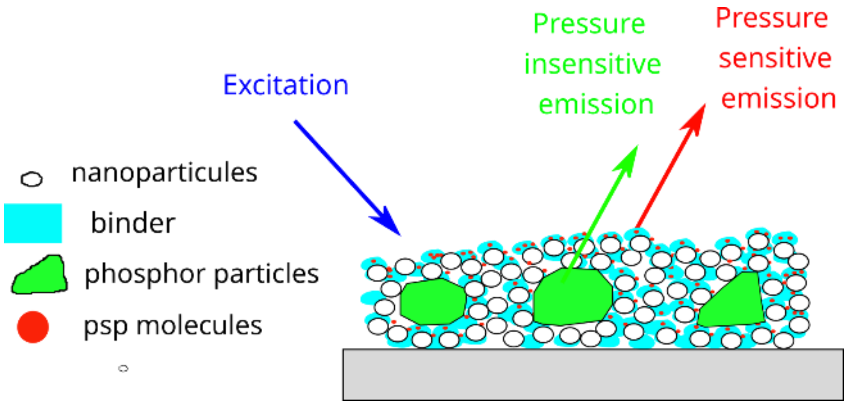


Temperature corrected unsteady PSP

O. Le Bourgeois, F. Nicolas, M. Couliou, B. Fond, *A temperature-corrected Ruthenium and inorganic phosphor-based fast responding pressure sensitive paint*, AIAA SciTech Forum, 2025.

→ Two-colour paint with a porous structure for fast response to pressure changes

- → Complete spectral separation of the emission not to diminish the pressure sensitivity
- → Inorganic component (phosphor) for the temperature channel to limit the photochemical interference effects
- → Same excitation source to simplify the experimental setup



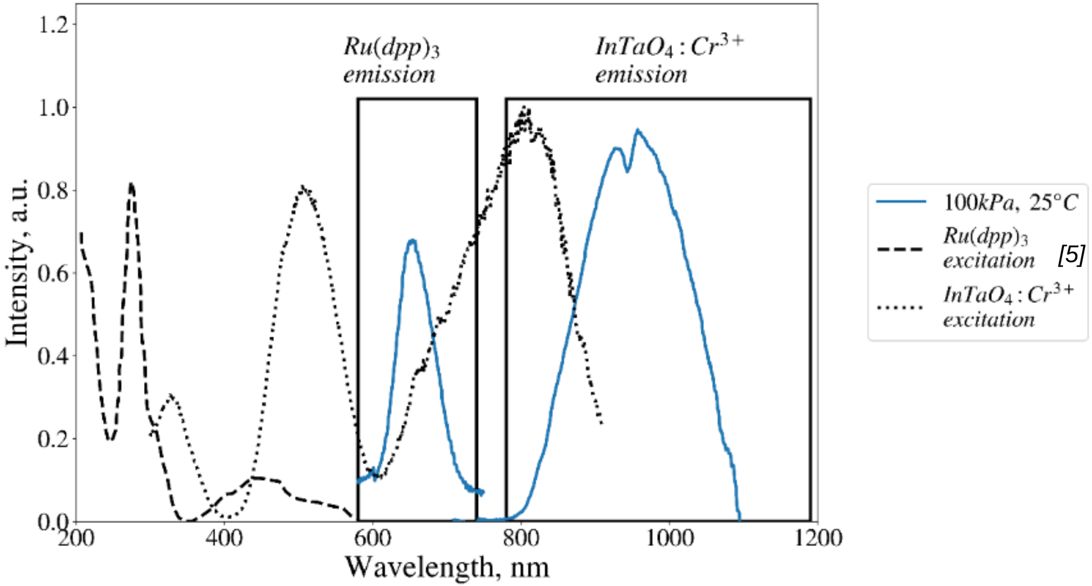
T corrected unsteady PSP

Paint formulation

[4] Qiu, L *et al.*, “Cr3+-Doped InTaO4 Phosphor for Multi-Mode Temperature Sensing with High Sensitivity in a Physiological Temperature Range,” *Inorganic Chemistry Frontiers*, 2022
[5] Liu, T., Sullivan, J. P., Asai, K., Klein, C., and Egami, Y., “Pressure and Temperature Sensitive Paints, Second Edition,” Berlin : Springer, Berlin, 2021.

- $Ru(dpp)_3$ as the pressure sensor, also temperature sensitive
- $InTaO_4:Cr^{3+}$ [4] as the temperature sensor → synthesised by solid-state reaction

→ Same excitation domain
→ Clear spectral separation of the emissions



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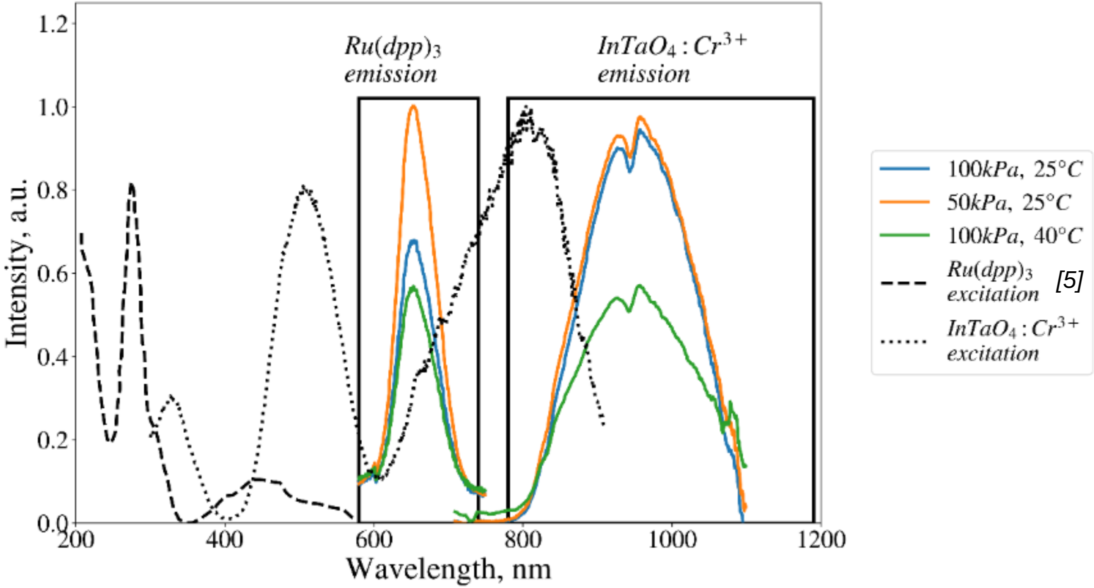
- $InTaO_4:Cr^{3+}$ [4] as the temperature sensor → synthesised by solid-state reaction

→ Same excitation domain
→ Clear spectral separation of the emissions

→ $InTaO_4:Cr^{3+}$ only temperature sensitive

Integrated in fast-response paint

- Hydrophobic TiO2 nanoparticles
- RTV118 as the polymer
- Toluene/DCM as solvents



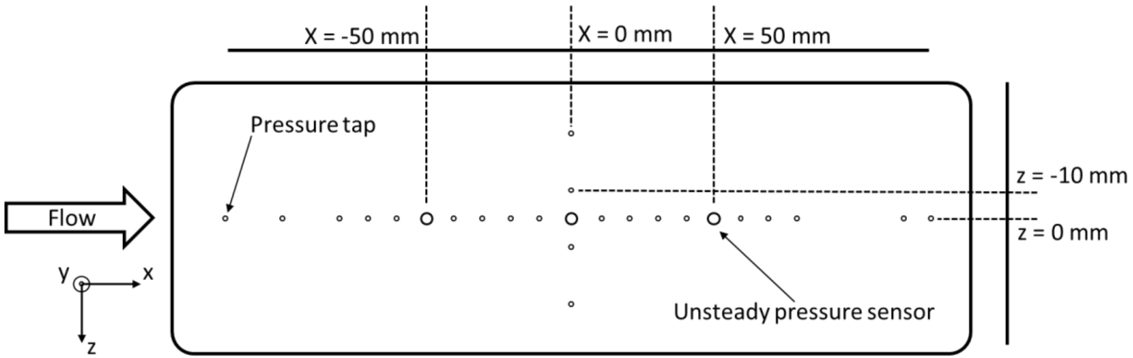
Meudon research transonic WTs: S8Ch

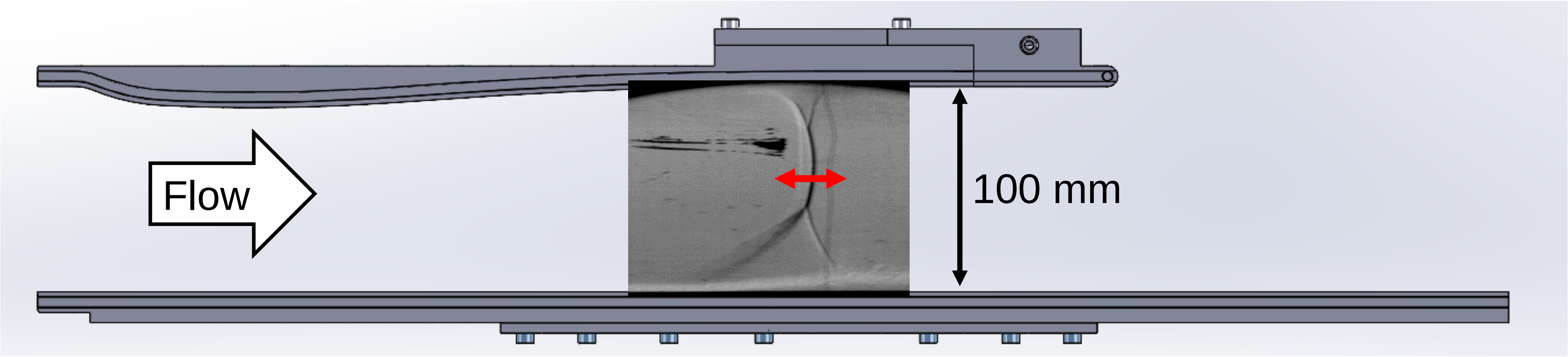
- Mach range: 0,5 < M < 0,8 and 1,4 < M < 2.0
- Atmospheric stagnation pressure and temperature
- Open-circuit, continuous operation
- Auxiliary pumping circuit
- Drying chamber
- Two independent test sections / wind-tunnels
- Slightly different dimensions depending on targeted conditions:
  - supersonic: 0,12 x 0,12m²
  - subsonic: 0,10 x 0,12m²

Temperature corrected unsteady PSP
WT setup

O. Le Bourgeois, F. Nicolas, M. Couliou, B. Fond, *A temperature-corrected Ruthenium and inorganic phosphor-based fast responding pressure sensitive paint*, AIAA SciTech Forum, 2025.

- Shock-wave boundary layer interaction at M = 1.36
- (Lower) plate size: 280mm x 95mm
- 22 pressure taps





Temperature corrected unsteady PSP

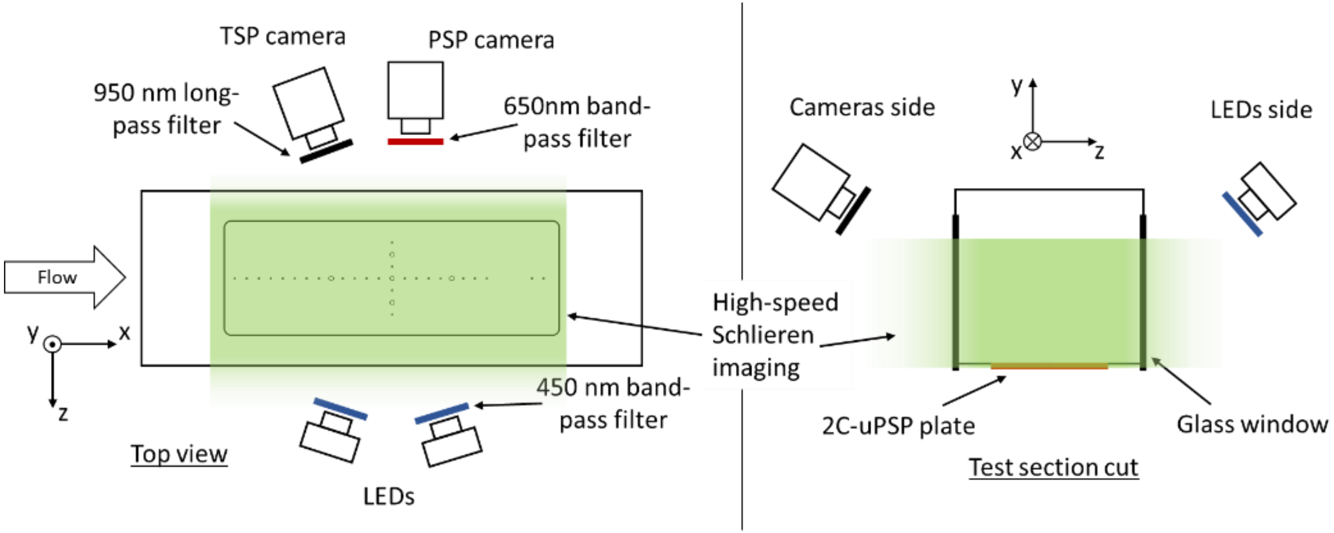
Optical setup

O. Le Bourgeois, F. Nicolas, M. Couliou, B. Fond, *A temperature-corrected Ruthenium and inorganic phosphor-based fast responding pressure sensitive paint*, AIAA SciTech Forum, 2025.

- High-speed schlieren
- 2 v2640 phantom cameras
- 2 blue HardSoft LEDs

PSP camera: 4800 Hz
TSP camera: 100 Hz

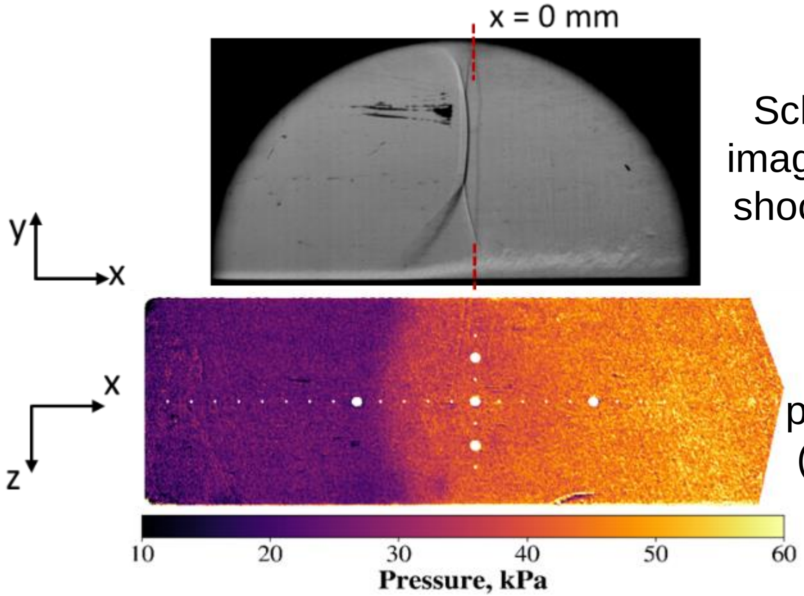
- 50mm, f#1.4 lenses
- ~6px/mm along x
- ~4px/mm along z



Temperature corrected unsteady PSP

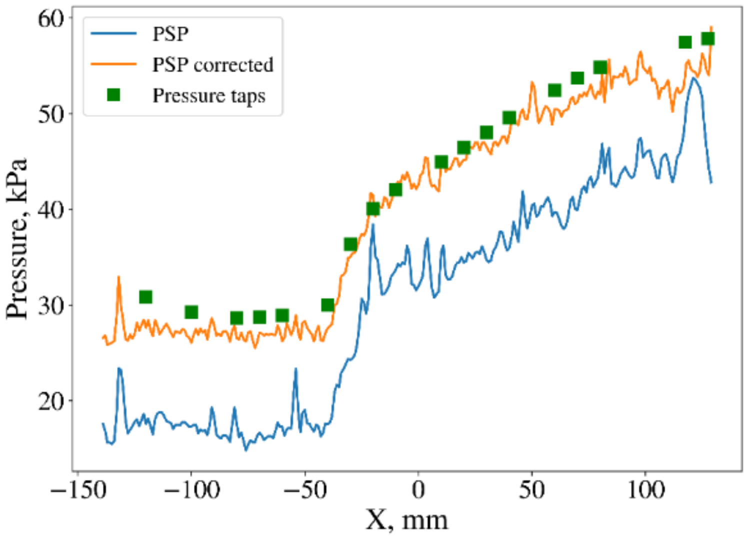
Results

O. Le Bourgeois, F. Nicolas, M. Couliou, B. Fond, *A temperature-corrected Ruthenium and inorganic phosphor-based fast responding pressure sensitive paint*, AIAA SciTech Forum, 2025.



Schlieren image of the shock wave

Corrected pressure field (single shot)



Pressure profiles at z = -4mm, average of 5px

→ Correct localisation of the shock

→ Efficient temperature correction

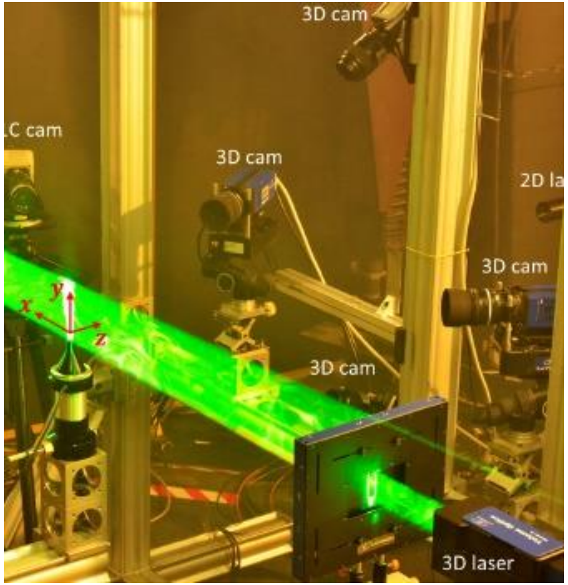
→ Small offset (<2kPa) remaining

Preparing our future WT tests

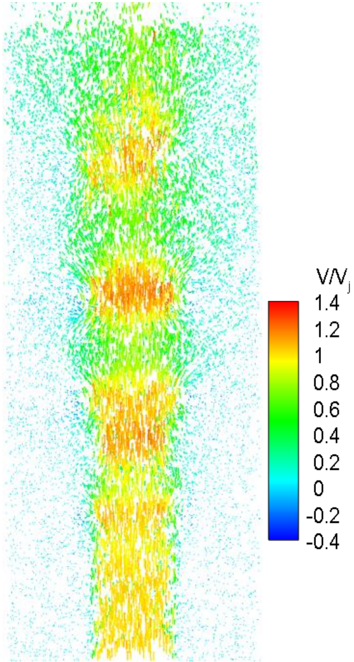
Further lab and hybrid experimental-numerical research

P. Cornic, B. Leclaire, F. Champagnat, G. Le Besnerais, A. Cheminet, C. Illoul, G. Losfeld, *Double-frame tomographic PTV at high seeding densities,* Experiments in Fluids, 61, 1-24, 2020.

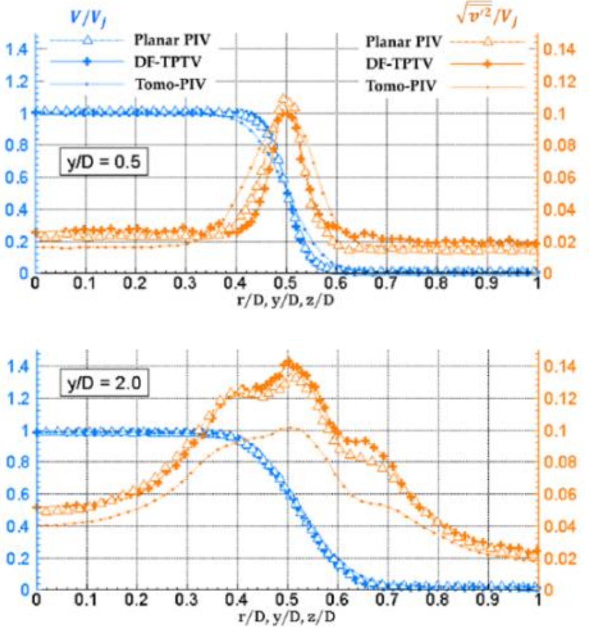
3D Particle Tracking Velocimetry



Experimental setup



Instantaneous vector field



Time and azimuthally averaged flows: comparison 3D PTV, 3D PIV, 2D PIV

RÉPUBLIQUE FRANÇAISE

ONERA

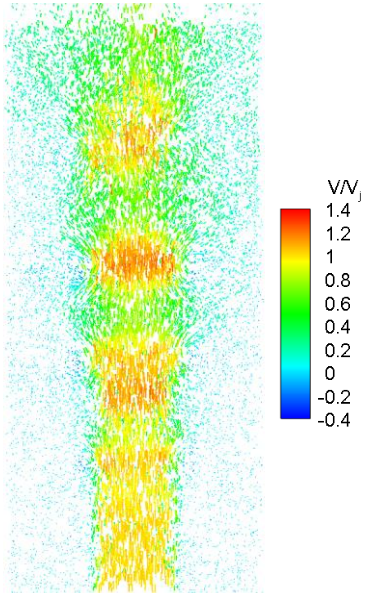
THE FRENCH AEROSPACE LAB

Preparing our future WT tests

Further lab and hybrid experimental-numerical research

V. Mons, O. Marquet, B. Leclaire, P. Cornic, F. Champagnat, *Dense velocity, pressure and Eulerian acceleration fields from single-instant scattered velocities through Navier-Stokes-based data Assimilation,* Meas. Sci. Technol. 33, 2022

measured data: $\boldsymbol{m}$



Objective: minimize

$$\min_{f} \left\{ J = \frac{1}{2} \| \boldsymbol{m} - \boldsymbol{h}(\boldsymbol{u}) \|^2 \right\}$$

h : measurement operator: mimics PTV

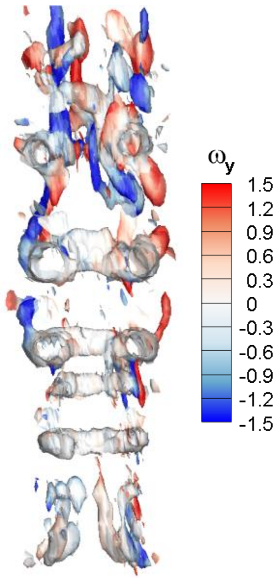
under incompressible Navier-Stokes constraint:

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

$$(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} - Re^{-1}\Delta \boldsymbol{u} + \nabla p = \boldsymbol{f}$$

… when minimum is reached, control parameter f yields $-\partial \boldsymbol{u}/\partial t$!

simulation : $\boldsymbol{u}$



Available: $\boldsymbol{u}$
at particles' positions only

Nice, but **variational optimization + DNS**
⇒ very expensive!

Available: $\boldsymbol{u}$, p, $\partial \boldsymbol{u}/\partial t$ on a regular grid
⇒ ∇u, eddies…

Preparing our future WT tests

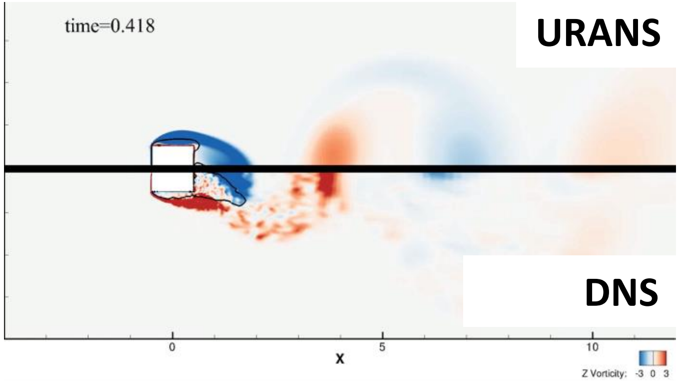
Further lab and hybrid experimental-numerical research

M. Zauner, V. Mons, O. Marquet, B. Leclaire, *Nudging-based data assimilation of the turbulent flow around a square cylinder,* J. Fluid Mech, 2022.

$$\boldsymbol{M}\frac{\partial \boldsymbol{q}}{\partial t} = \boldsymbol{R}(\boldsymbol{q})$$

URANS motion equations

$Re = 22\,000$



- URANS: cost effective (but crude)! ⇒ Improving it thanks to data?…

Preparing our future WT tests

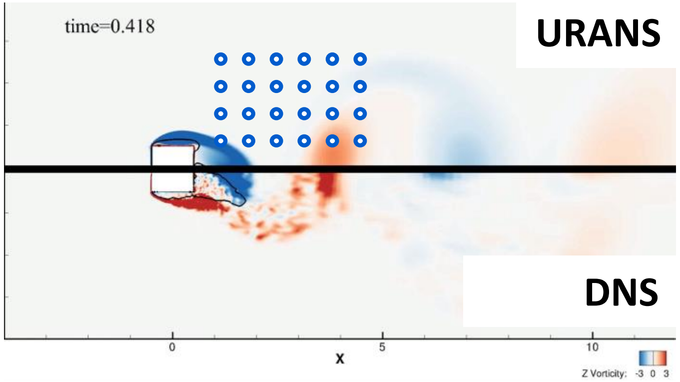
Further lab and hybrid experimental-numerical research

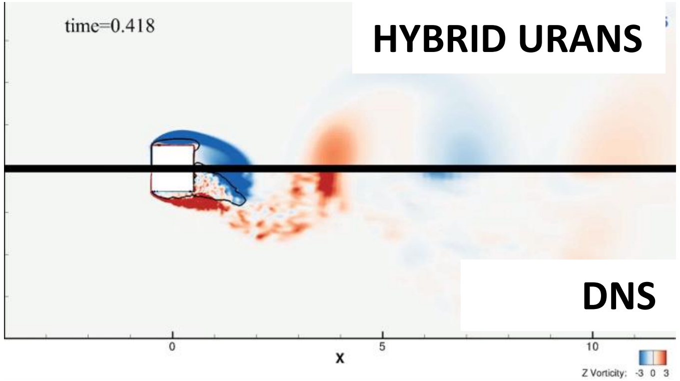
M. Zauner, V. Mons, O. Marquet, B. Leclaire, *Nudging-based data assimilation of the turbulent flow around a square cylinder,* J. Fluid Mech, 2022.

To handle high Re unsteady flows: « nudging »

Data forcing using measurement operator

$$\boldsymbol{M}\frac{\partial \boldsymbol{q}}{\partial t} = \boldsymbol{R}(\boldsymbol{q}) + \alpha\, h_m^T\,(u_m - h_m(\boldsymbol{q})\,)$$





- URANS: cost effective (but crude)! ⇒ Improving it thanks to data
- Hybrid URANS (« nudged »): added source term enforcing closeness to data
- **Still cost effective but corrected**: **strong potential for Reynolds number upscaling!**

Preparing our future WT tests

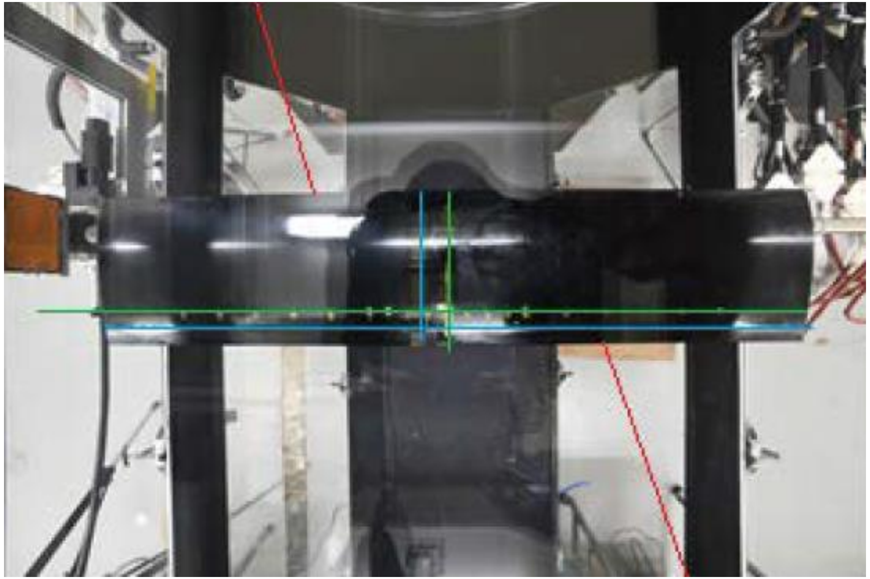
Further lab and hybrid experimental-numerical research

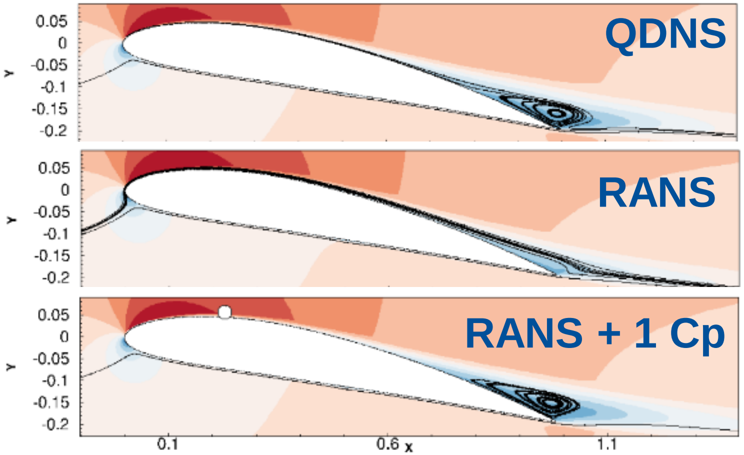
C. Tayeh, V. Mons, O. Marquet, Data assimilation of turbulent separated flows using single synthetic and experimental wall-pressure data, 2023, https://hal.science/hal-04251656/

(Steady) RANS simulation: variational approach is affordable!

Assimilation-based correction of RANS with a single Cp measurement:

NACA 4412 2D profile @ Meudon S2L low-speed WT, $Re = 350{,}000$





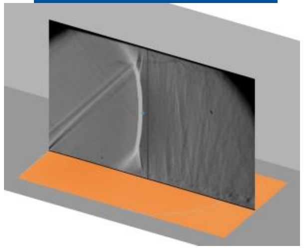
Acknowledgements

Vincent Brion & Geoffrey Tanguy (*resp. heads of DAAA Meudon & Lille WT units*), Jean-Charles Marie Couliou, Benoît Fond, Georgios Kasapis, Orian Le Bourgeois, Arnaud Lepage, Mathieu Lugrin, Olivier Marquet, Vincent Mons, Sylvain Morilhat, François Nicolas, Loïc Sombaert, Cynthia Tayeh, Cédric Thémiot, Markus Zauner…

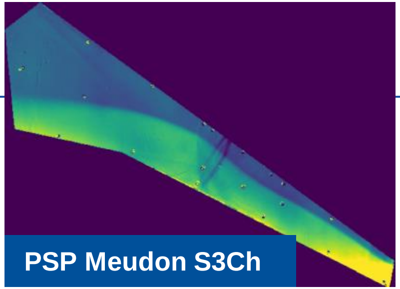
Questions?

Wall forces Meudon R1Ch

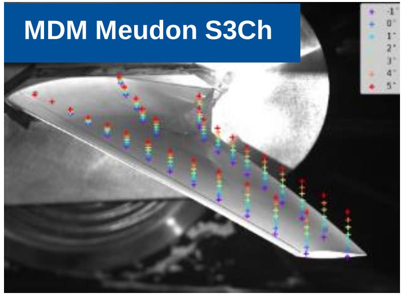
Test section p’ Meudon R1Ch



High-speed Schlieren S8Ch



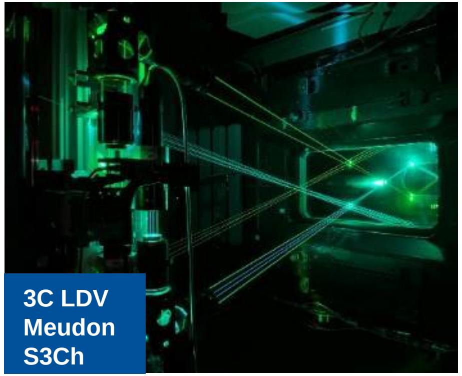
PSP Meudon S3Ch



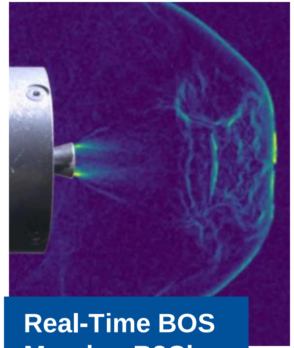
MDM Meudon S3Ch

Viscous oils Meudon S3Ch

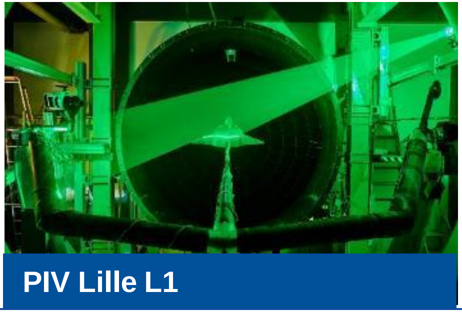
Lille INTROH test bench



3C LDV Meudon S3Ch



Real-Time BOS Meudon R2Ch



PIV Lille L1