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On the importance of accurate simulation of attached boundary layers in the frame of hybrid RANS/LES & WMLES

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Outline

- Initial background of ZDES: turbulence modelling for space launcher configurations

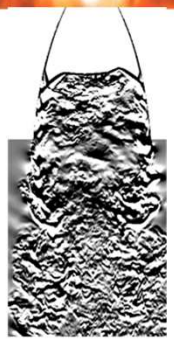
$\rightarrow$ Treatment of attached TBL

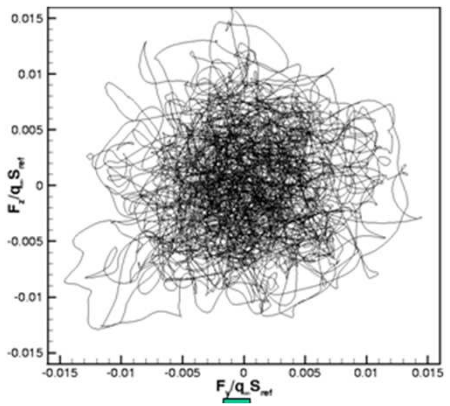
- Option 1: 100% RANS
- Option 2: WMLES
- Concluding remarks

Context: prediction of side-loads on space launchers









Importance of unsteady aerodynamic flow predictions

Strong fluctuations in the loads taken up by the Vulcain engine actuators

Side-Loads (inside the nozzle)

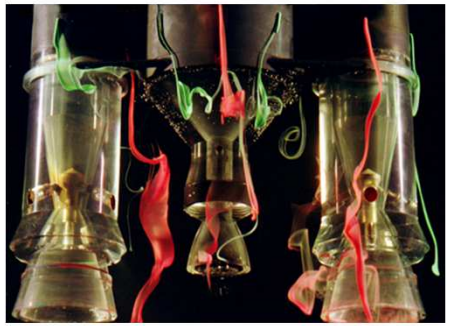
Buffet excitation « buffeting »

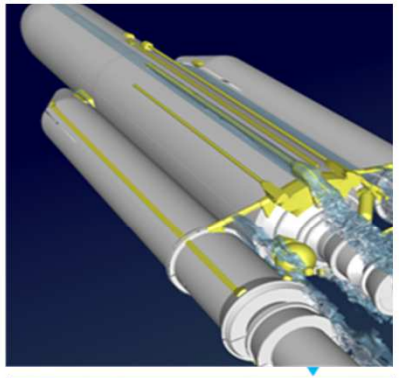
experiments

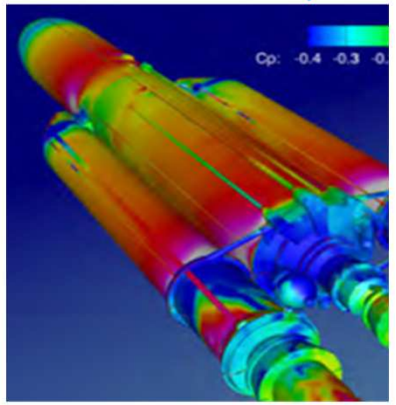
Numerical approach

NS 3D and unsteady simulation on a sufficient duration ..

Use of hybrid RANS/LES

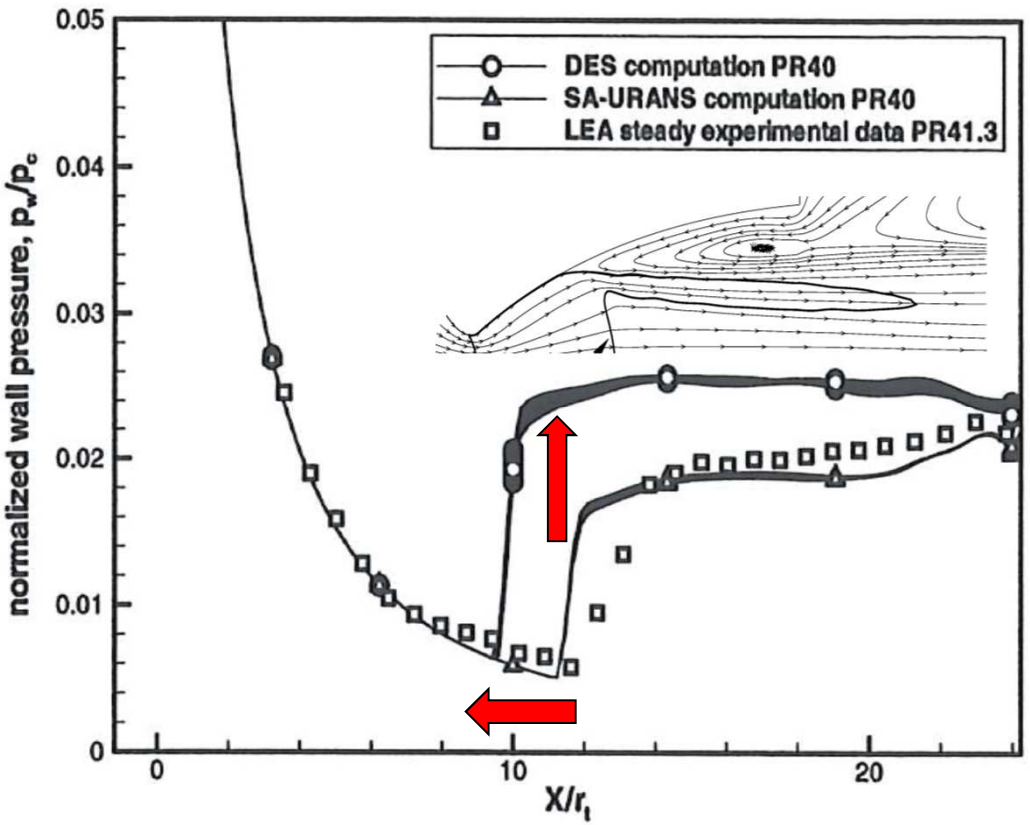






S. Deck, A.T. NGuyen, AIAA J, 2004
P.E.Weiss, S. Deck, Comp.& Fluids, 2018

Questions of paramount importance



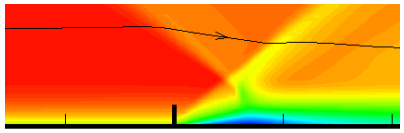
« 1st GIS », S.Deck PhD 2002

Insufficient RANS protection:

- ➢ C_f **underestimated, relaminarisation**
- ➢ **Grid Induced Separation (GIS)**

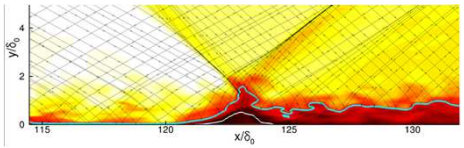
Q1:Treatment of TBL ?

- Option 1: 100% RANS



+ simple and cost-efficient in massive flow separation
- quick switching to LES difficult

- Option 2: WMLES



+ mild/incipient flow separation
- Finer mesh, necessity to inject resolved turbulence

Q2: zonal or non-zonal treatment of turbulence

Zonal or non-Zonal treatment of turbulence?

- A fully automatic method (i.e. without user input) is desirable to reduce the decision load on the user but “utopian” in a near/mid-term future

- The authors clearly advocate the use of a zonal treatment of turbulence to handle complex configurations, even if the decision load is increased, for several reasons:
  1. An automatic method (black-box push button) is not desirable (though very tempting!)

     → If the fully automatic model fails, the user is helpless (potential reasons for failures include complex geometries and physics on “real-life” grids)

     → An automatic method can convey a misleading feeling of easiness. Even perfectly idiot-proof models require a significant level of expertise from the user which cannot be replaced by the computer so far… (e.g. the design of a hybrid RANS/LES grid is far from being trivial)

     → In the frame of wall-turbulence resolving simulations (e.g. on a whole aircraft) , the activation of LES content in the TBL will be necessarily embedded in the computational domain (i.e. zonal!)

  2. A zonal non-automatic approach alleviates the user load during computation monitoring and post-processing since the behavior of the model is known in advance

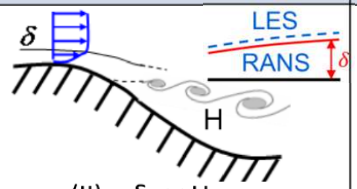
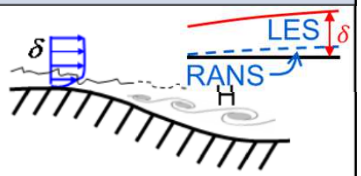
  3. It is worth stressing that a zonal approach also permits operation in an automatic mode (but the reverse is not true). Such a functionality is provided by ZDES mode 2

- Current best-practices within the hybrid RANS/LES community suggest that the authors’ point of view is now increasingly shared by other teams

Advanced turbulence modeling

Zonal Detached Eddy Simulation (ZDES) developed by ONERA since 2002, extensively validated (>100 peer-reviewed publications), routinely used by the aerospace industry

- **ZDES: Multi-resolution approach, i.e., covers the full range of modeling from RANS to LES**
  - **Objective: use LES only where/when required**
  - **Zonal approach to allow flexibility but can be used as a global automatic model**
  - **3 functioning *modes* according to the flow problem of interest**

	Zonal Detached Eddy Simulation (ZDES)		
	Mode 1	Mode 2	Mode 3
Flow category	 (I) : δ << H	 (II) : δ << H	 (III) : δ = O(H) or δ > H
Applications	Base flow, free shear flows, spoilers, steps, slat/flap cove, etc.	Buffet, flaps, duct flows, nacelle intake, etc.	Corner flows, turbulent boundary layer, separation onset on high lift devices, shallow separations, etc.

« Automatic » mode **« WMLES » mode**

- **To guide the user through the simulation process, a system based around flow taxonomies is proposed**
- **Within ZDES, three specific hybrid length scale, also called modes, are optimized, on three typical flow topologies**

$$\tilde{d}_{ZDES} = \tilde{d}_{mode}\left(\tilde{\Delta}, d_w, U_{i,j}, \tilde{\nu}, \frac{\partial\tilde{\nu}}{\partial n}, \frac{\partial||\omega||}{\partial n}\right)$$
$$mode = 0, 1, 2, 3$$

Refs: **Deck (Theo. & Comp. Fluid Dynamics, 2012), Deck (AIAA J., 43(11), 2005)**
Deck & Renard (J. Comp. Phys., 2020)

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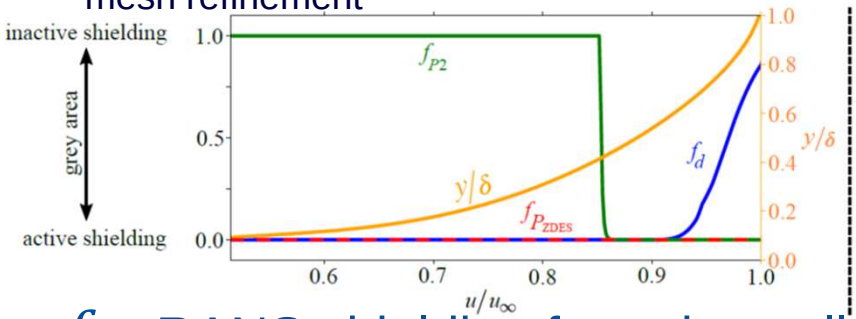
RANS protection of attached boundary layers

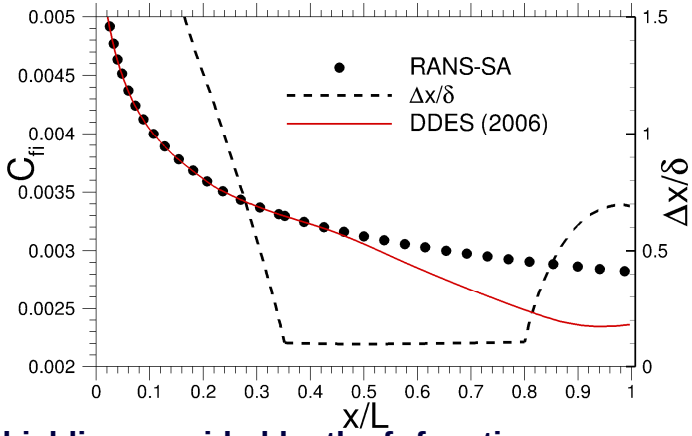
HRLES methods are distinguished by their protection function

- DES (1997) : No specific RANS shielding function
- DDES (2006): f_d
- ZDES mode 2 (2020):

$$f_{P_{ZDES}} = f_d(1-(1-f_{P2})f_R)$$

→ the model shields the whole BL (incl. wake regions) incl. infinite mesh refinement





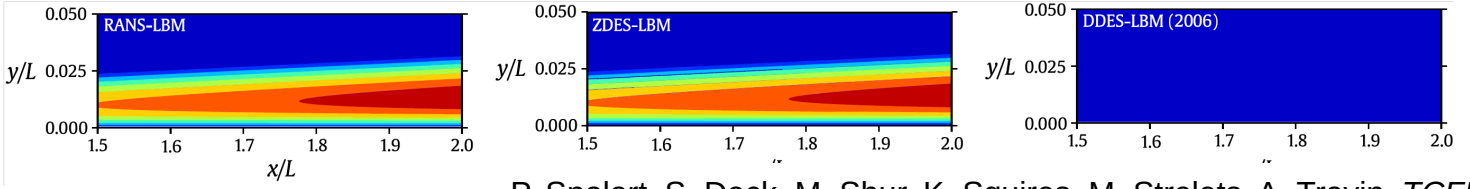
→ **shielding provided by the f_d function becomes insufficient when the grid spacing in the streamwise direction, say Δx<0.5δ where δ is the local boundary layer thickness.**

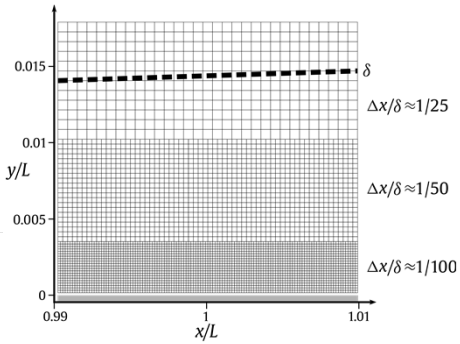
→ **Tricky problem !**

f_d: RANS shielding from the wall to the log-layer

f_{P2}: extends the shielding from the log to the outer-layer

f_R: prevents the RANS shielding of mixing layers





(Courtesy of J. Husson)

P. Spalart, S. Deck, M. Shur, K. Squires, M. Strelets, A. Travin, *TCFD, 2006*

S. Deck & N. Renard, *Journal of Computational Physics, 2020*

J. Husson, M. Terracol, S. Deck, T. Legarrec, *Journal of Computational Physics, 2024*

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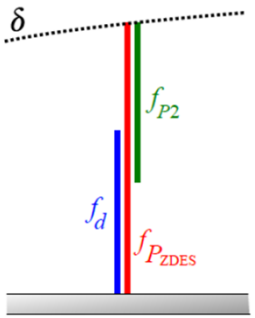
ZDES mode 2 (2020): key elements

Deck & Renard, *Towards an enhanced protection of attached boundary layers in hybrid RANS/LES methods*, JCP, 2020

Objectives

1. RANS protection of attached TBL ∀ mesh refinement & pressure gradient
   NB separation ⇒ LES
2. Protection ≥ ZDES mode 2 (2012) by construction
3. Smallest possible delay in the development of instabilities
4. Full compatibility with ZDES mode 1 and 3 (LES zone)

$$f_{P_{ZDES}} = f_d(1-(1-f_{P2})f_R)$$



⇒ Historic sensor kept (log zone)
1st protection function (f_d)

$$r_d = \frac{\tilde{\nu}+\nu}{\sqrt{u_{i,j}u_{i,j}}\kappa^2 d_w^2}$$

⇒ **3 new elements:**

a) wake layer sensor
2nd protection function (f_{P2})

$$\mathcal{G}_{\tilde{\nu}} = \frac{C_3 \max(0, -\partial\tilde{\nu}/\partial n)}{\sqrt{u_{i,j}u_{i,j}}\kappa d_w}$$

$$\underline{n} = \frac{\underline{\nabla} d_w}{|\underline{\nabla} d_w|}$$

b) separation sensor
Inhibition function (f_R)

$$\mathcal{G}_\Omega = \frac{\partial(|\omega|)}{\partial n}\sqrt{\frac{\tilde{\nu}}{\left(\sqrt{u_{i,j}u_{i,j}}\right)^3}}$$

c) destruction enhancement in grey areas

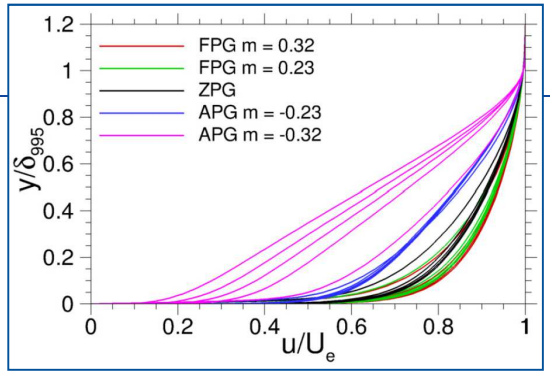
$$f_w = (1-\text{test}_w)\, f_w(\tilde{\nu}, d_w, \tilde{S}) + \text{test}_w((1-\text{test}_\Delta)\cdot 100 + \text{test}_\Delta f_{w,\text{mode 1}})$$

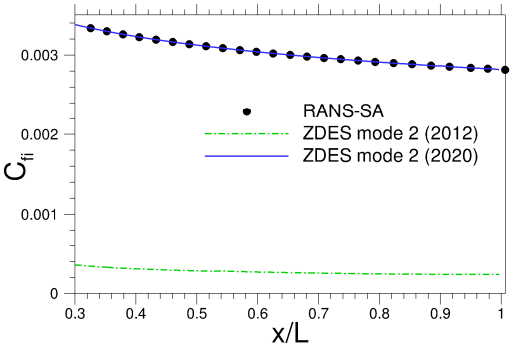
ZDES mode 2 (2020): a few comments

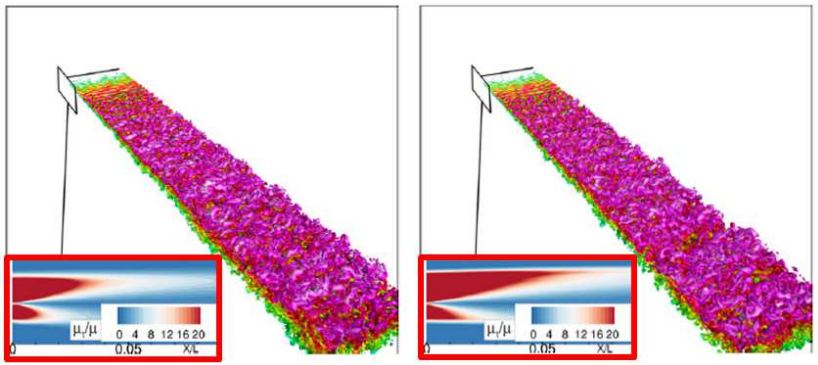
- Constants calibrated to reach all 4 objectives of the model, sensors non-dimensionalised (Reynolds number effect taken into account)
- The values of the constants must not be modified
- For the RANS treatment of a separated region, use mode 0
- Transitional boundary layers should be preferably treated with mode 0
- The safest protection is obtained by initialising the simulation from a RANS field (the sensors use the pseudo eddy-viscosity)
- ZDES mode 2 (2020) is however capable of rebuilding a RANS boundary layer previously treated partially in LES (2nd protection function)

- RANS shielding up to infinite mesh refinement (ZPGFPTBL with $C_{DES}\Delta = 0$)

- Mixing Layer and Backward Facing Step: resolved turbulence content developing nearly as quickly as with ZDES mode 2 (2012)



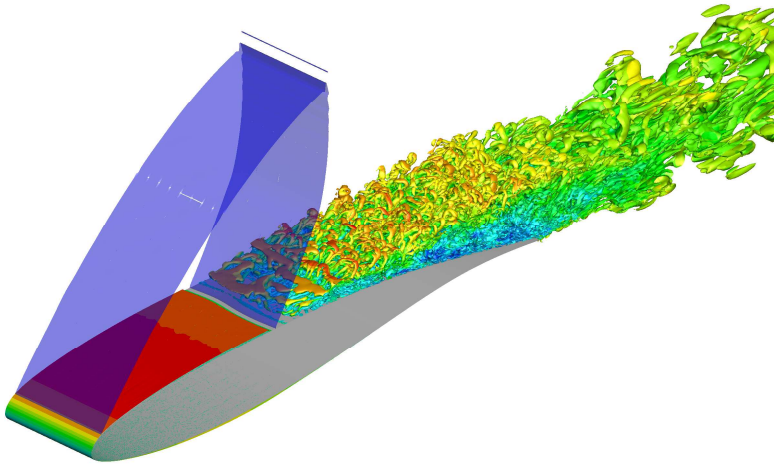




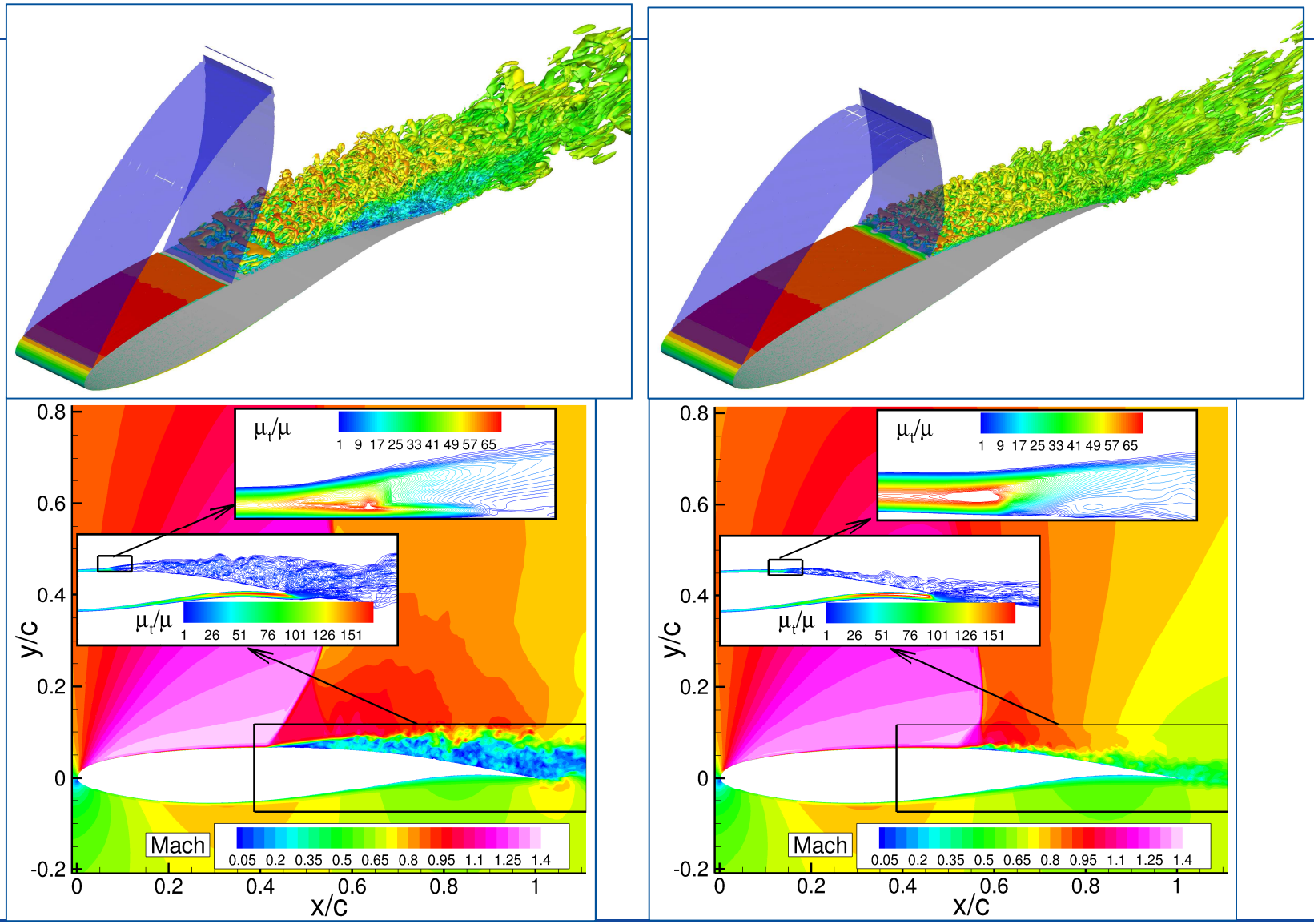
(b) ZDES mode 2 (2012, $C_1 = 8$) (d) ZDES mode 2 (2020)

Application to the transonic buffet around a 2D airfoil

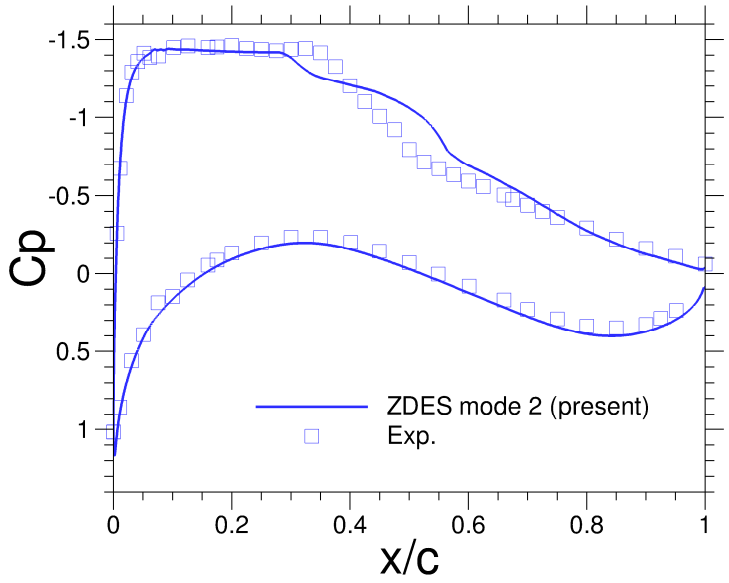
- ZDES mode 2 (2020) simulation of flow around **OAT15A supercritical airfoil** in transonic buffet conditions (same as in the experiment by Jacquin et al. 2009)
- Transition fixed at x/c = 7% on both sides
- $Re_c = 3 \cdot 10^6$, $\mathrm{M}_\infty = 0.73$, $\alpha = 3.5°$
- Numerical domain **span = $\mathbf{0.2\ c}$**, $\Delta x^+ = 150$, $\Delta z^+ = 100$ (**typical WMLES grid** resolutions ⇒ challenging protection)
- Total grid count $\mathbf{58.4 \cdot 10^6}$ **points** (compared with $440 \cdot 10^6$ for the WMLES by Fukushima & Kawai (2018) with a span of only $0.065\ c$).
- Physical time step $\Delta t = 2 \cdot 10^{-7} s$, implicit time integration scheme converged with 6 Newton inner iterations
- Unsteady signal stored over almost 8 periods (about 350 000 CPU hours, whole simulation lasted over 500 000 CPU hours)

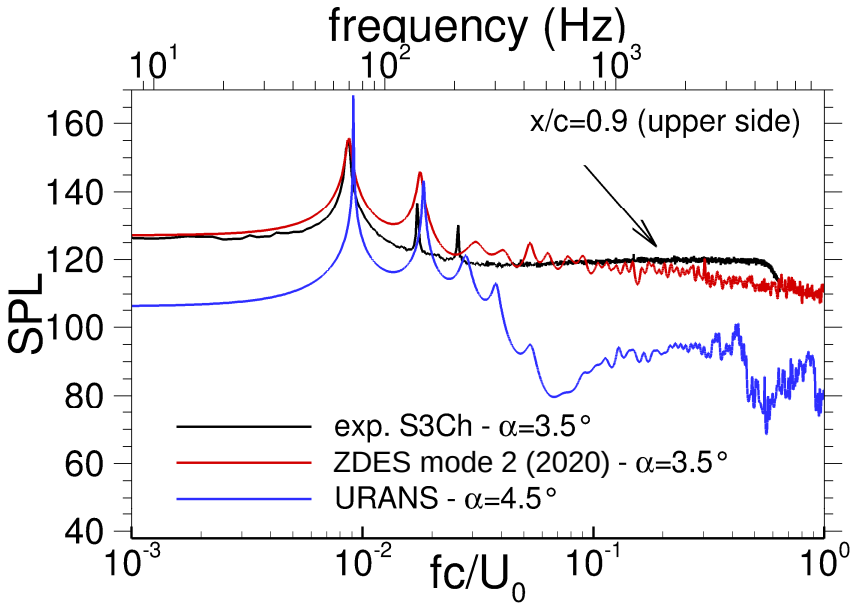


OAT15A: instantaneous flow



OAT15A: wall pressure spectra



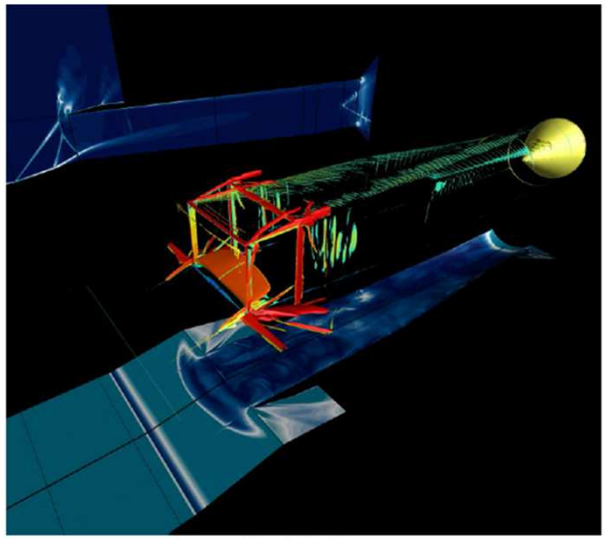


- PSD estimated by auto-regressive (AR) model based on Burg's method (short signal, spectral peaks)
- Upper side broadband (LES content)
- URANS: buffet onset at higher α, no broadband spectral content

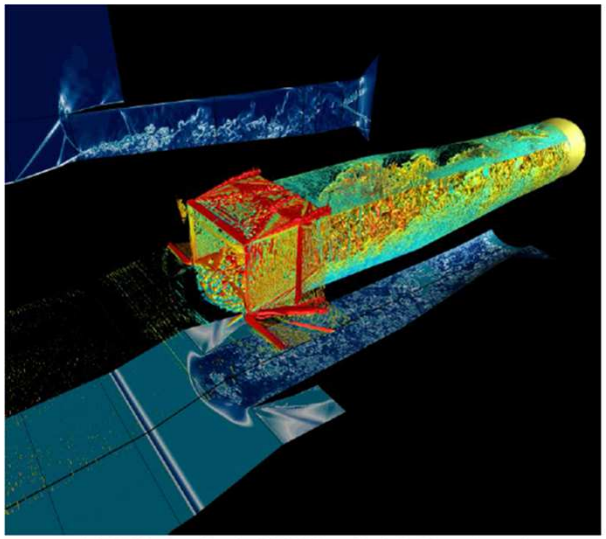
Example of a supersonic inlet flow: initialisation aspects

- Mach 1.8 inlet with precompression ramp
- Very fine mesh ($\Delta x^+ = 100, \Delta z^+ = 100$)
- Failure of original DDES shielding (ZDES mode 2 (2012))
- ZDES mode 2 (2020) successfully shields attached BLs
- Convergence to the same mean state after initialisation from RANS or from ZDES mode 2 (2012)

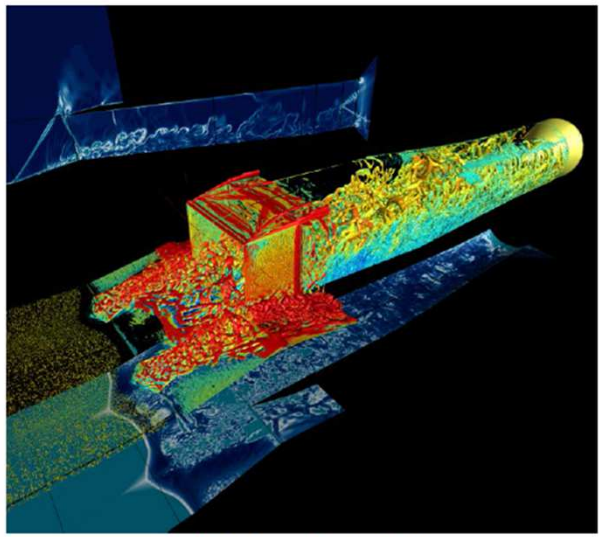
Weiss & Deck, 2018



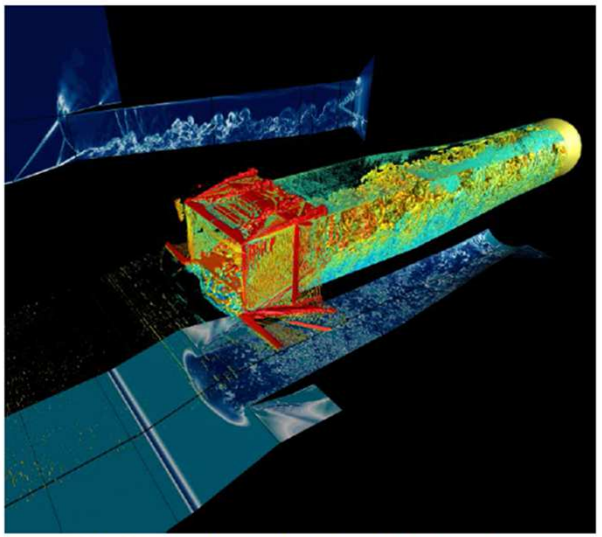
RANS-SA



ZDES mode 2 (2020) – Initialisation 1

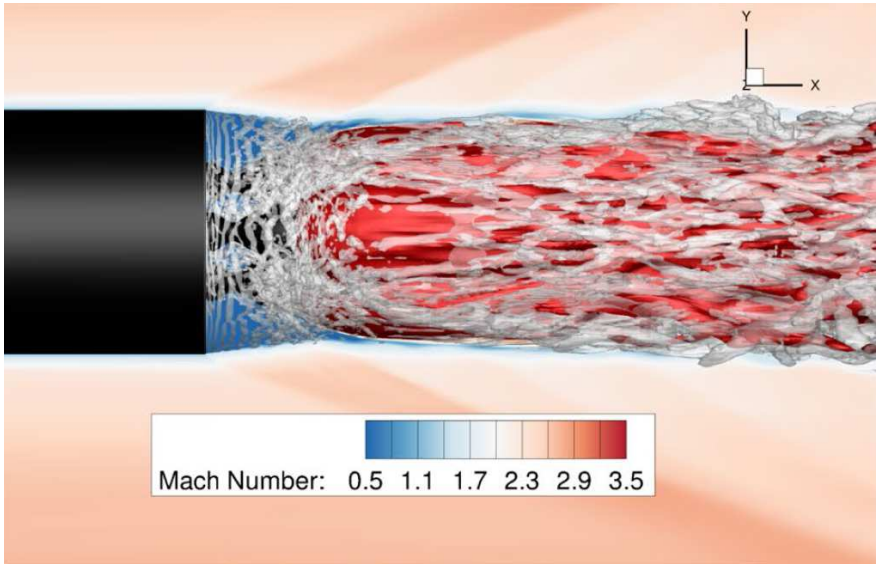


ZDES mode 2 (2012)

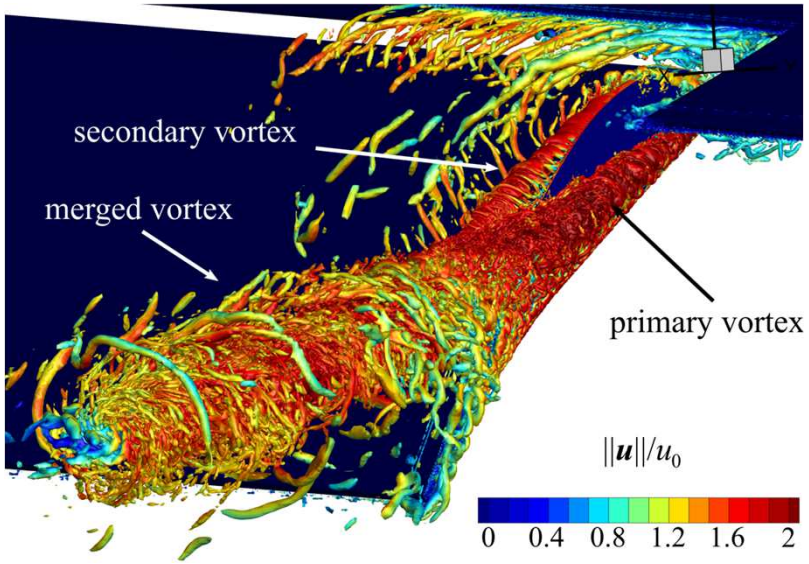


ZDES mode 2 (2020) – Initialisation 2

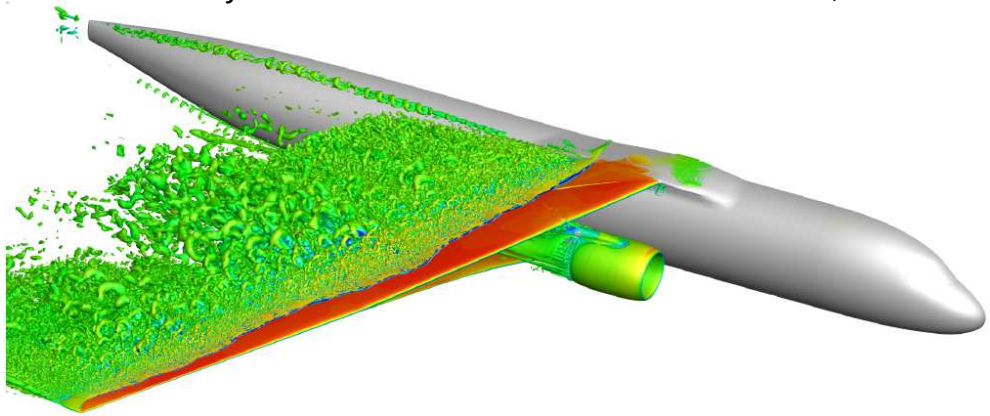
Examples of applications of ZDES mode 2 (2020)



Wake of the afterbody of a multi-nozzle space launcher configuration, Reynaud et al., On the Use of Bi-species ZDES for Multi-nozzle Space Launcher Configurations, FTC 2022



Flap side-edge flow prediction, Husson et al., Numerical study of Flap Side-Edge vortex based on the combination of Zonal Detached Eddy Simulation and lattice-Boltzmann method, AIAA 2024



Transonic Buffet for the Boeing Transonic Truss-Braced Wing Aircraft, Browne et al., Simulating Transonic Buffet Aerodynamics for the Boeing Transonic Truss-Braced Wing Aircraft, AIAA 2024

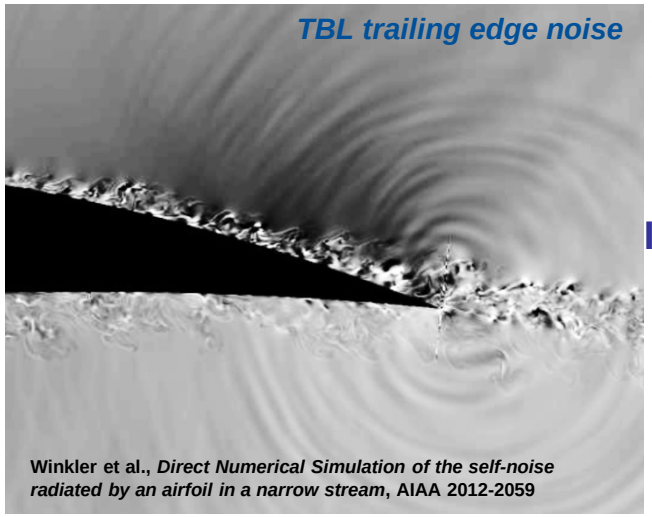
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Typical flow situations where WMLES might prove useful



Winkler et al., *Direct Numerical Simulation of the self-noise radiated by an airfoil in a narrow stream*, AIAA 2012-2059

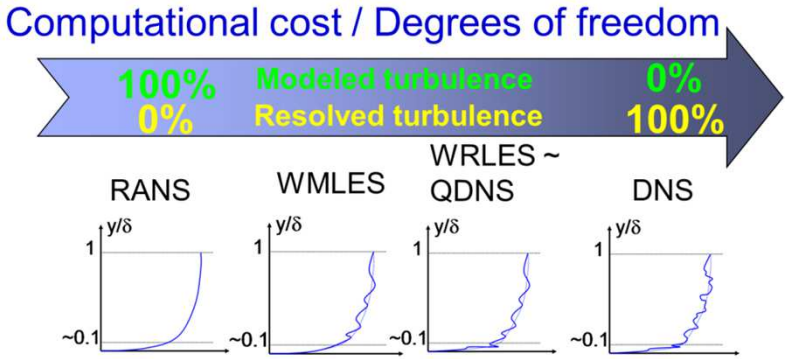
- Flow dominated by history of upstream boundary layer
- Applications (unsteady loads, aeroacoustics…)

$$CL = IL\ (\sim 0.1\delta) + OL\ (\sim 0.9\delta)$$

Important cost of the inner layer (99% of the total cost at high Re !)

- The only way to perform practical LES of high Re TBL is by computing the outer layer only (WMLES)
- Δ can be determined by the outer flow eddies so that it becomes weakly Re dependent
- Counterpart: the effect of the wall layer must be modelled because the grid cannot resolve the QSV vortices that transfer momentum in this region of the flow





Inner layer ($y/\delta \leq 0.1$)	*modeled*	*modeled*	*mostly resolved*	*fully resolved*
Outer layer	*modeled*	*mostly resolved*	*mostly resolved*	*fully resolved*

- Direct Numerical Simulation (DNS) : prohibitive cost
- Wall-Resolved Large Eddy Simulation (WRLES): Quasi-DNS (inner zone)



- **Wall-Modelled LES (WMLES) : affordable at high Reynolds numbers (modelled inner zone)**

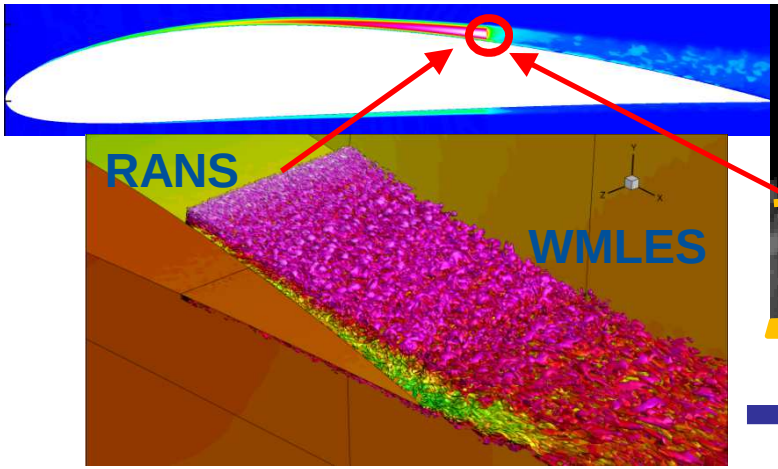
S. Deck, N. Renard, R. Laraufie, P. Sagaut, Physics of Fluids, *2014*

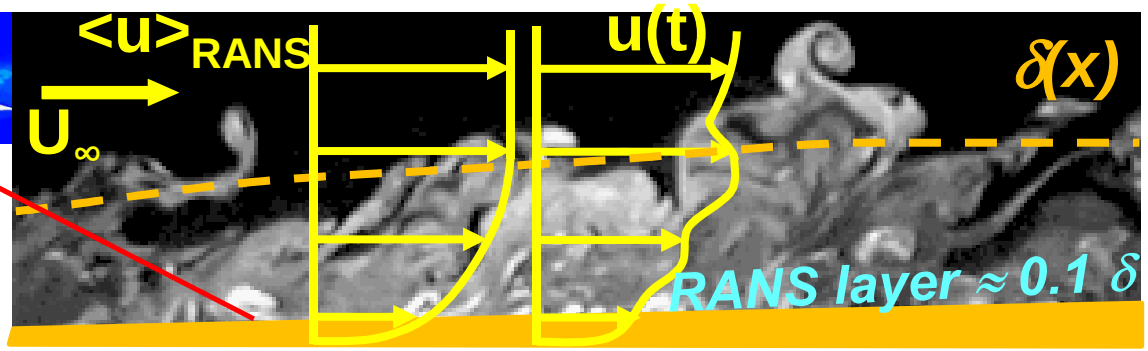
Typical flow situations where WMLES might prove useful

- **Meth. 1: "Classical WMLES"**
  Wall-law/Set of simplified near-wall equations
- **Meth. 2: Hybrid RANS/LES methods**
  - ➢ simpler extension to complex geometries (not necessary to apply WMLES everywhere)
  - ➢ Intrinsic capacity to include the near-wall spanwise effects (eg $\frac{\partial P}{\partial z} \neq 0$ not easily taken into account with a wall-law)

→ **RANS/LES interface:**

- Active RANS/LES interface: stochastic forcing, additive filtering, heterogeneous filtering…
- **Passive RANS/LES interface**
  - ➢ IDDES, ZDES mode 3…
  - ➢ may result in issues such as *log-layer mismatch*





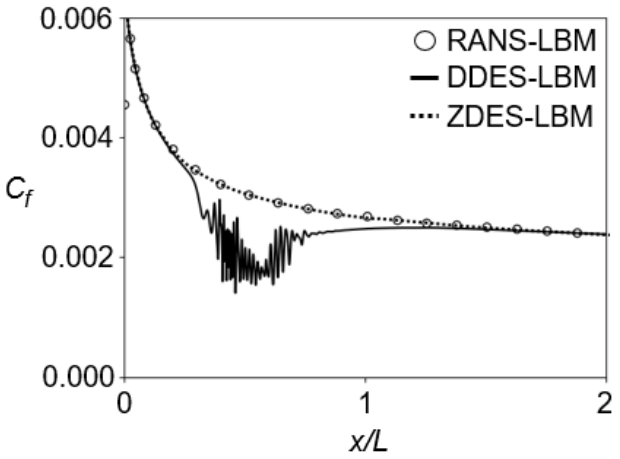
ZDES Mode 3:
Wall-Modelled LES,
Wall-Resolved LES capability

$$(N_{xyz})_{DNS} \propto (N_{xyz})^2_{WMLES}$$

Challenges: turbulence « stimulation », adaptation length, « log-layer mismatch», spurious acoustic noise, compressible effect, curvilinear extension

Estimating the contribution of the wall law to the prediction of skin friction in WMLES

- Does the **wall law** fully determine the **skin friction**?
  - ➢ Not 100% since the input **depends on the resolved turbulence above the wall**
  - ➢ Dramatic example: LBM-DDES with wall law on fine mesh ($\frac{\Delta x}{\delta} \approx \frac{1}{100}$): turbulent wall law does not prevent relaminarisation.



  - ➢ To quantify the contribution of the wall law (also of the RANS model in RANS/LES strategies), need to **decompose the contributions of turbulence to mean skin friction** as a function of wall distance and physical mechanisms → fundamental studies with the same flow solvers as the industrial applications
- RD decomposition of mean skin friction (Renard & Deck, 2016, *A theoretical decomposition of mean skin friction generation into physical phenomena across the boundary layer*, JFM)

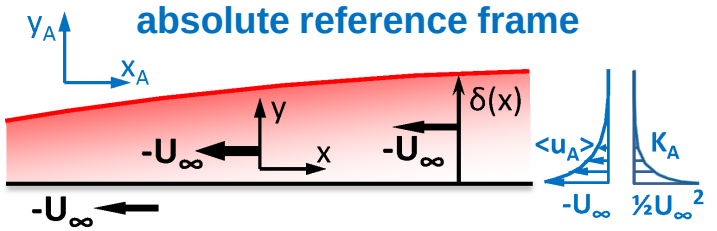
Decomposition of mean skin friction: RD identity

- Budget of mean streamwise kinetic energy K_A in absolute reference frame integrated over wall distance:

$$C_f = \underbrace{\frac{2}{U_\infty^3}\int_0^\infty \nu\left(\frac{\partial\langle u\rangle}{\partial y}\right)^2 dy}_{C_{f,a}} + \underbrace{\frac{2}{U_\infty^3}\int_0^\infty -\langle u'v'\rangle\frac{\partial\langle u\rangle}{\partial y}dy}_{C_{f,b}} + \underbrace{\frac{2}{U_\infty^3}\int_0^\infty (\langle u\rangle - U_\infty)\frac{\partial}{\partial y}\left(\frac{\tau}{\rho}\right)dy}_{C_{f,c}}$$

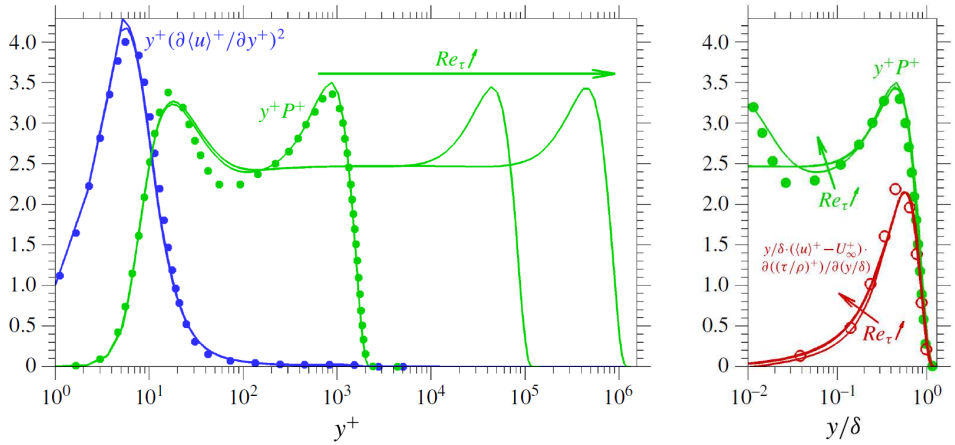
➢ Energy provided by the wall to the fluid:
  - Heat (direct dissipation)
  - Turbulent Kinetic Energy (production)
  - Mean streamwise kinetic energy

$$\frac{\tau}{\rho} = \nu\frac{\partial\langle u\rangle}{\partial y} - \langle u'v'\rangle = \nu\frac{\partial\langle u_A\rangle}{\partial y_A} - \langle u'_A v'_A\rangle$$



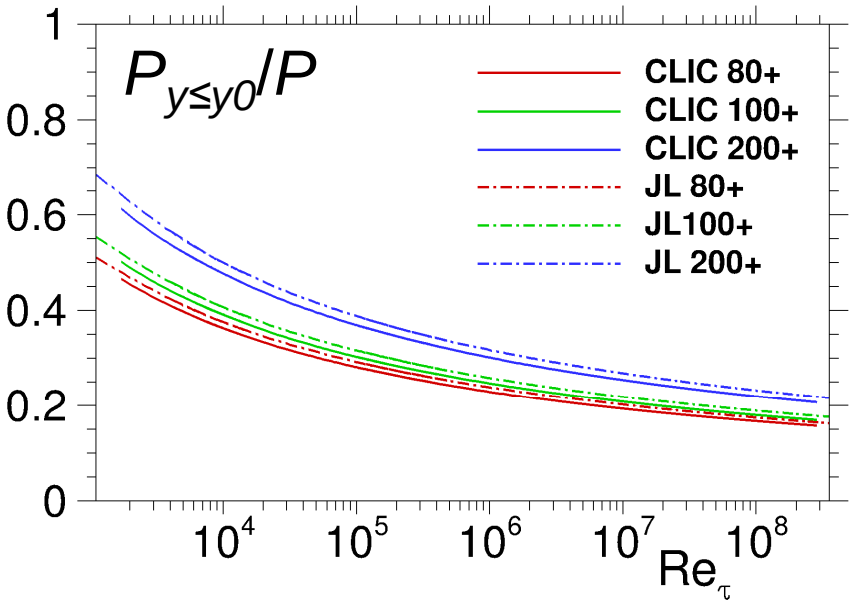
- The TKE production term ($C_{f,b}$) dominates at high Reynolds numbers (logarithmic region)

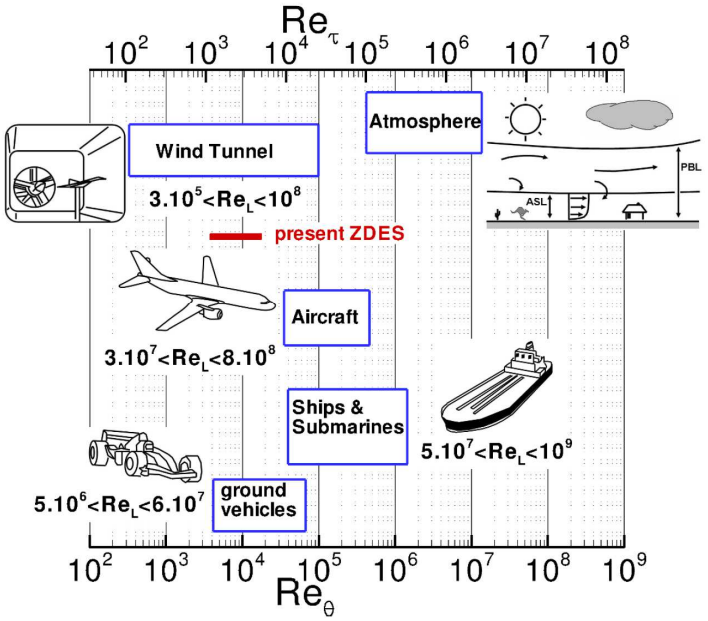
➢ Contribution to mean skin friction analysed by decomposing the TKE production



Estimating the contribution of the wall law to skin friction (upper bound)

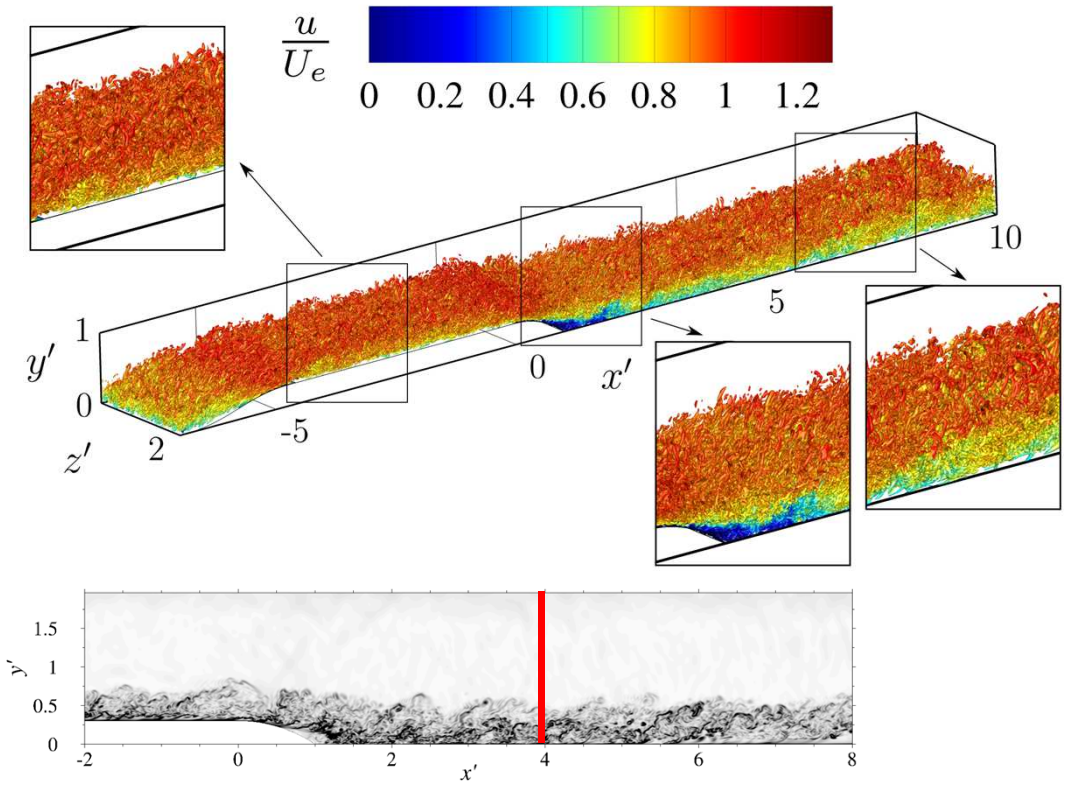
- Simplified vision: the wall law is 'modelling' the TKE production *P* below a height y_0^+ whereas *P* is 'resolved' above → Upper bound estimate of the contribution of the wall law $P_{y\leq y0}/P$
- The 'weight' of the wall law vanishes at infinite Reynolds number. Around 30-50% at applicative Reynolds numbers.
- Confirms that injecting resolved turbulence when needed is crucial for WMLES, the wall law cannot compensate for the absence of turbulence



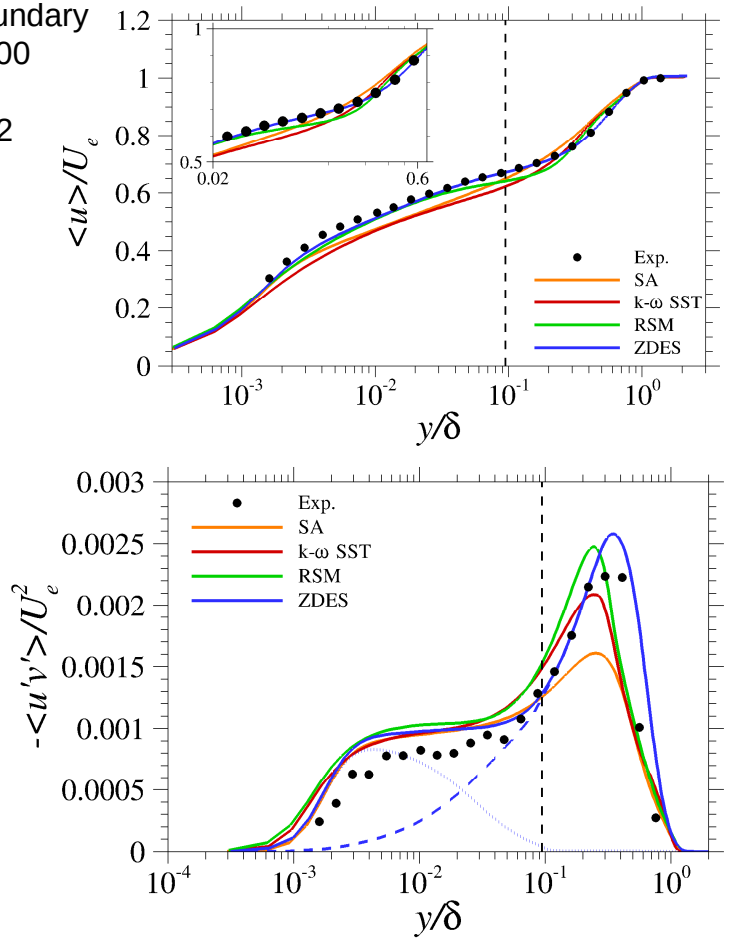


Application of ZDES mode 3 to a mild flow separation and recovery

- Song & Eaton (2004) experiment
- $Re_{\theta,ref} = 13200 : Re_{\theta,max} = 23000$
  - $N_{xyz,ZDES} = 288 \times 10^6$
  - $N_{xyz,WRLES} = 16 \times 10^9$
  - $N_{xyz,DNS} = 320 \times 10^9$



- Better prediction of recovery region than RANS models including RSM
- Vaquero et al., Outer layer turbulence dynamics in a high-Reynolds-number boundary layer up to $Re_\theta \approx 24000$ recovering from mild separation, JFM, 2022



Outlook

- ZDES developed by ONERA : RANS/LES operational on a wide range of applications
  - ✓ Zonal approach is the main strength of this method
  - ✓ Computational resources and user inputs focused in the regions of interest, RANS elsewhere (contrary to WMLES where turbulence resolved in every boundary layer)
  - ✓ Limits the overall computational cost and complexity (the user knows in advance the behavior of the model)

- Massively separated flows: mandatory to shield the attached BL in RANS for arbitrary grid refinement and to avoid delay in the formation of instabilities. Automatic detection of attached turbulent boundary layers for RANS protection is crucial.
  - ✓ RANS/LES methods are mainly distinguished by their protection function
  - ✓ The protection function $f_{P_{ZDES}}$ of ZDES mode 2 (2020) is the only published local formulation satisfying the conditions. Routinely used by the industry (Dassault Aviation, Airbus, MBDA, Safran…).

- Near wall turbulence at high Reynolds number remains challenging (e.g. ZDES mode 3, WMLES)
  - ✓ Better understanding and treatment of the RANS/LES interface and/or of the wall law in WMLES
  - ✓ Necessity to inject resolved turbulence: adaptation distance, turbulence reconstruction
  - ✓ Investigation of wall turbulence for high Reynolds numbers Re_θ>10000
  - ✓ Development of guidelines for the reliable use in applied aerodynamics/acoustics

Because of the broad scale separation at high Reynolds numbers, wall-modelling is mandatory (either RANS or WMLES) to keep the computational cost within reach, making the use of hybrid RANS/LES techniques essential (pacing item in aerospace engineering & a research subject)!

Questions

