Advanced Simulations for unsteady turbulent flows in applied aerodynamics

Sébastien DECK
Applied Aerodynamics Department
sebastien.deck@onera.fr

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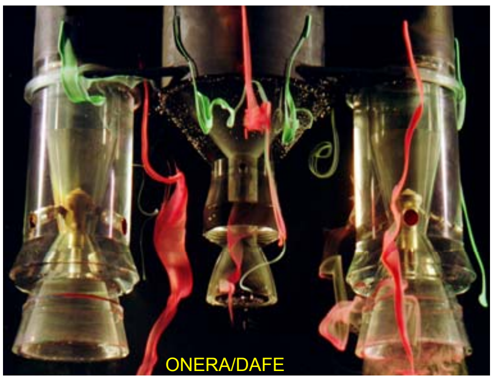
THE FRENCH AEROSPACE LAB

return on innovation

Unsteadiness in aerodynamics

- RANS/URANS massively used in design (optimization, uncertainties) and for multidisciplinary coupling (flight mechanics, optics, …)
- When the three-dimensional turbulent unsteady field is required…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Serious implications
→ Achievable performance
→ Safety – Acoustic environment
→ accurate prediction ASAP in the design

Direct Numerical Simulation (DNS)

- DNS concept: “capture” all active scales

1. **Turbulence *production* (instabilities, …)**
2. **Inter scale energy *transfer* (Kinetic Energy Cascade)**
3. **Turbulent *dissipation* (viscous effects)**

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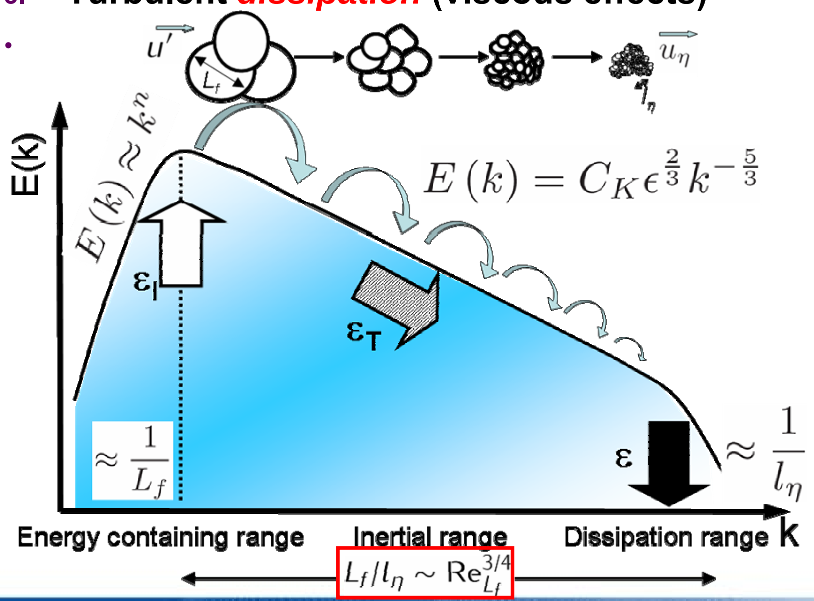

HIT TKE spectrum

$$\overline{k} = \int_0^\infty E(k)\,dk$$

(adapted from Sagaut, Deck, Terracol, 2006)

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Direct Numerical Simulation. Cont’d

$$\text{computing time} \propto N_{xyz}.N_t \propto \tilde{C}.\mathrm{Re}_L^3$$

[µs/point/itération]

- at the wall: $\Delta x \sim l_\eta \sim$ w.u. $\sim 10^{-6}$m
- L~50m, $S_{wing} \approx 1\ m^2$/pax $\approx 10^{12}$ w.u.^{2}/pax
- $(\Delta x^+ \Delta z^+)_{DNS} \approx 100$ w.u.^{2}
- $N_{xyz} > 10^{16}$ (2080, Spalart et al.)
- is it necessary ?
- need for a compromise between resolved physics/CPU cost

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Contents

- Scale separation. Basics of RANS and LES.
- Hybrid RANS LES approaches. DDES and ZDES.
- Examples of recent applications.
- Further discussion and remaining challenges.
- Conclusions.

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Mode reduction

- **Key idea:** cost reduction = small scale elimination
- **Therefore:**
  - Need for a scale separation operator
  - Resolved scales and unresolved scales
  - Model for resolved/unresolved scale interactions
- **Families of operators**
  - Statistical average → RANS
  - Small scale elimination →LES
  - Combination →Hybrid RANS/LES

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Second Symposium "Simulation of Wing and Nacelle Stall", June 22nd - 23rd, 2010, Braunschweig, Germany

Scale separation

$$f(\mathbf{x}, t) \quad \mathbf{x} = (x_1, x_2, x_3)^T$$

$\mathcal{F}$: scale separation operator

$$f = \overline{f} + f'$$

$$\overline{f} = \mathcal{F}(f)$$

Resolved part of *f*

$$f' = (Id - \mathcal{F})(f)$$

Unresolved part of *f*

This decomposition will be applied to the aerodynamic variables
Such as the velocity field ***u*** or the pressure *P*

Scale separation. Cont'd

Global idea of all cost reduction approaches → consider only the resolved field $\overline{f}$

Introduction of a mathematical closure to account for the unresolved field f'

$NS(\overline{f})$ **looks similar to** $NS(f)$

Some additional terms appear in the equations which account for ALL missing interactions between the resolved and the unresolved fields

Scale separation. Cont'd

$$\nabla \cdot \mathbf{u} = 0$$
$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nu \nabla^2 \mathbf{u}$$

$$\mathbf{u} = (u_1, u_2, u_3)^T$$
$$p = P/\rho$$

$$[a,b]\, f = a \circ b(f) - b \circ a(f)$$
$$\mathcal{B}(\mathbf{u}, \mathbf{v}) = \mathbf{u} \otimes \mathbf{v}$$

$$\nabla \cdot \overline{\mathbf{u}} = -A_1$$
$$\frac{\partial}{\partial t}\overline{\mathbf{u}} + \nabla \cdot (\overline{\mathbf{u}} \otimes \overline{\mathbf{u}}) = -\nabla \overline{p} + \nu \nabla^2 \overline{\mathbf{u}} - (A_2 + A_3 + A_4)$$

with

$$A_1 = [\mathcal{F}, \nabla \cdot]\, \mathbf{u}$$
$$A_2 = \nabla \cdot [\mathcal{F}, \mathcal{B}]\, (\mathbf{u}, \mathbf{u})$$
$$A_3 = [\mathcal{F}, \nabla \cdot]\, \mathcal{B}(\mathbf{u}, \mathbf{u}) + [\mathcal{F}, \nabla]\, p + \nu \left[\mathcal{F}, \nabla^2\right] \mathbf{u}$$
$$A_4 = \left[\mathcal{F}, \frac{\partial}{\partial t}\right] \mathbf{u}$$

- A_1 à A_4 additive functions of the original field and cannot be computed directly
- A_1, A_3, A_4 : possible commutation errors between opérators $\mathcal{F}$ and ∂_t , ∂_i
- *SSO chosen such that it commutes with differential operators* (A_1=A_3=A_4=0) …

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Scale separation. Cont'd

$$f = \overline{f} + f'$$

RANS formalism: $\overline{f} = \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{i=N} f_i$

$$\nabla \cdot \overline{\mathbf{u}} = 0$$
$$\frac{\partial}{\partial t}\overline{\mathbf{u}} + \nabla \cdot (\overline{\mathbf{u}} \otimes \overline{\mathbf{u}}) = -\nabla \overline{p} + \nu \nabla^2 \overline{\mathbf{u}} - \nabla \cdot \tau_{RANS}$$

LES formalism: $\overline{f}(\mathbf{x}, t) = G \star f(\mathbf{x}, t)$

$$= \int_0^{+\infty} \int_\Omega G(\overline{\Delta}(\mathbf{x}, t), \mathbf{x} - \xi, t - t').f(\xi, t').d\xi.dt'$$

$$\nabla \cdot \overline{\mathbf{u}} = 0$$
$$\frac{\partial}{\partial t}\overline{\mathbf{u}} + \nabla \cdot (\overline{\mathbf{u}} \otimes \overline{\mathbf{u}}) = -\nabla \overline{p} + \nu \nabla^2 \overline{\mathbf{u}} - \nabla \cdot \tau_{SGS}$$

→RANS & LES equations are formally identical but with fundamentally different scales

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Scale separation. Cont'd

$$\tau_{RANS} = \overline{\mathbf{u}' \otimes \mathbf{u}'}$$

→ A mathematical closure has to be introduced to represent the effect of the Reynolds stresses (first order closures, second-order analysis, …)

$$\tau_{SGS} = \overline{\mathbf{u}' \otimes \mathbf{u}'} - \overline{\mathbf{u}'} \otimes \overline{\mathbf{u}'}$$

→ Need for model for the interaction of the non resolved scales on the resolved scales

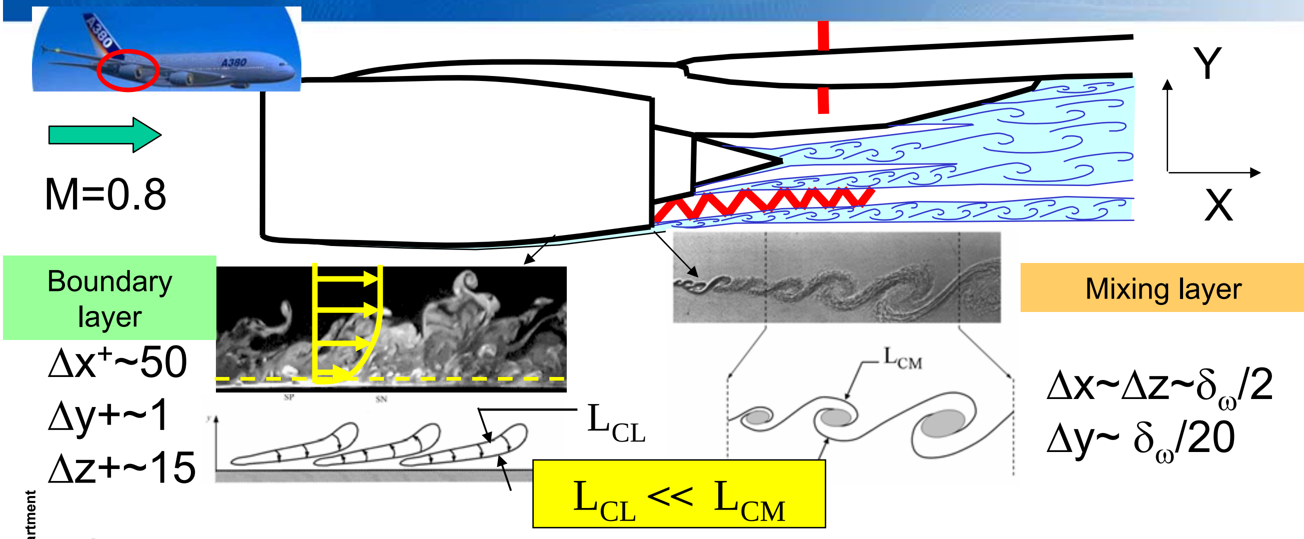
$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\nu_t \overline{S}_{ij}$$

Towards hybrid RANS/LES …

- switch in eddy/subgrid viscosity
- Direct change in subgrid viscosity scaling

Contents

Turbulence modelling : the large scales and LES. Production mechanisms.



260 m/s

0 m/s ---------------- Lx=1m

1 u.p.=υ/u_τ=2.5μm

Boundary layer

RANS : $\Delta x^+ \sim 500$ $\Delta y^+ \sim 1$ $\Delta z^+ \sim 1000$ → 1.3 mm × 2.5μm × 2.6 mm

LES : $\Delta x^+ \sim 50$ $\Delta y^+ \sim 1$ $\Delta z^+ \sim 15$ → 0.13 mm × 2.5μm × 37 μm

Mixing layer

LES : $\Delta x \sim \Delta z \sim \delta_\omega/2$ $\Delta y \sim \delta_\omega/20$ → 17 mm × 1.7mm × 17 mm

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Motivations of hybrid RANS/LES

Motivation : combine the best features of RANS and LES

RANS	LES
• attached flow	• separated flow
• low computational cost	• high computational cost

Hybrid RANS/LES

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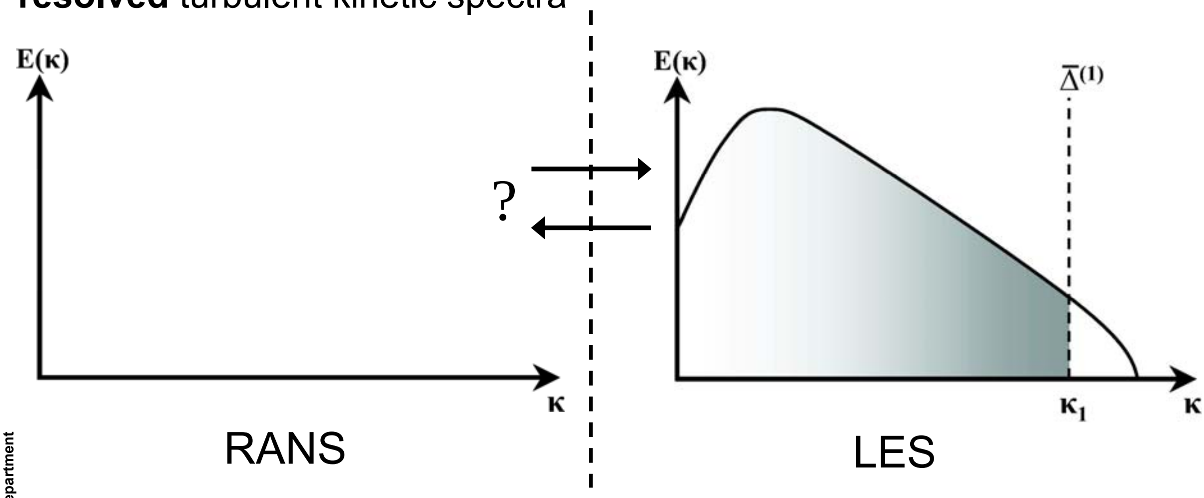
Motivations of hybrid RANS/LES (cont'd)

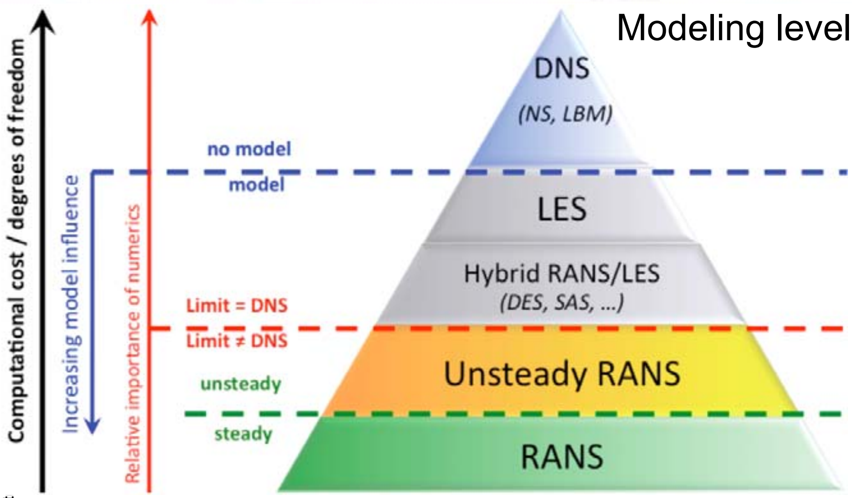
resolved turbulent kinetic spectra



- Very different frequency content between RANS and LES approaches
- Jump in the wave number content of the solution through the interface
- Additional difficulty : **no precise definition of the effective filter operator**

Note: numerical schemes → additional dissipation …
The scheme acts as a numerical filter which damps the highest resolved frequencies

Classification of unsteady approaches



Modeling level ≡ Compromise solution (physics / CPU cost)

Level of modeling/readiness

- global methods: continuous treatment of the flow variables at the interface
  → LES content generated progressively through a grey zone

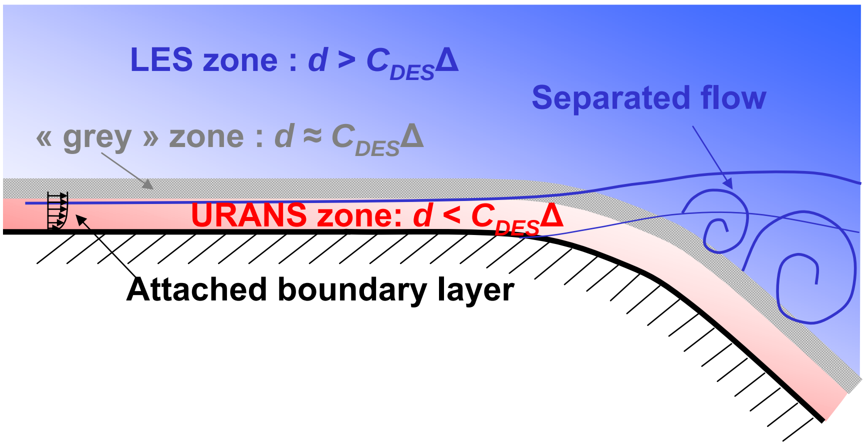
zonal methods: discontinuous treatment of the RANS/LES interface
  → definition of interface variables to construct a transfer operator at the interface

For a complete review, see *Sagaut P., Deck S., Terracol, M. (2006) Multiscale and Multiresolution approaches in turbulence. Imperial College Press, UK, 356 pp*

Detached Eddy Simulation – Modelled Stress Depletion – Grid Induced Separation

DES97 (Spalart et al. , 1997) $\tilde{\upsilon} \sim S\tilde{d}^{2}$ $\quad \tilde{d} = \max(d, C_{DES}\Delta) \quad \Delta = \max(\Delta_x, \Delta_y, \Delta_z)$

- natural use in thin boundary layers and in massive separation



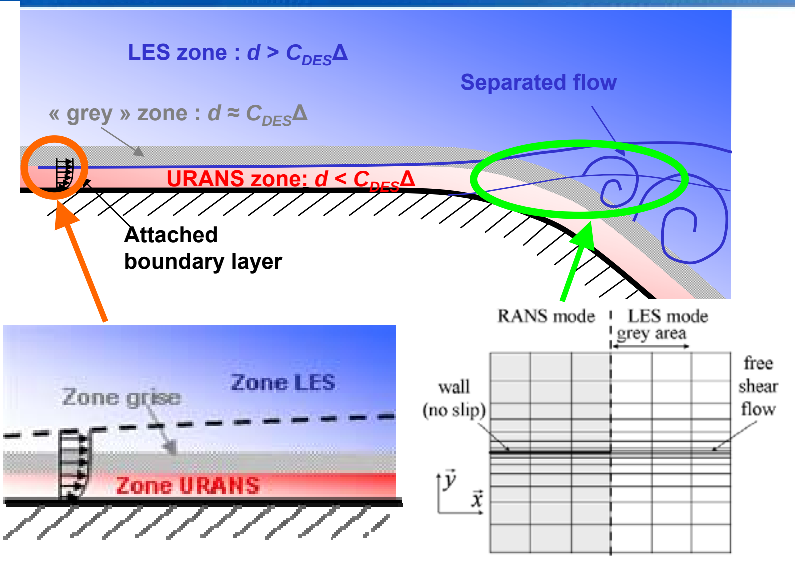
•The needs of different flow regions places conflicting demands on the grid

→ $\Delta_{tangential} > \delta$ requirement may be easily violated in industrial applications

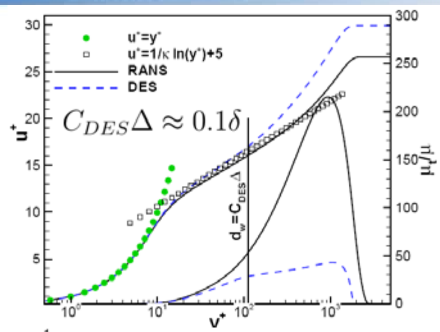
→isotropic LES cells + structured grid grid refinement in regions not intended to be handled by LES

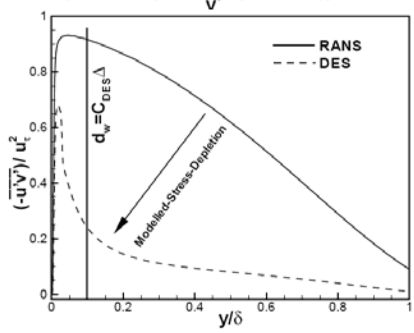
(NB: practically unavoidable in regions of high geometric curvature and/or thick BLs)

Detached Eddy Simulation – Modelled Stress Depletion – Grid Induced Separation



(b) “longitudinally induced MSD”





- Weakened υ_t → Modelled Stress Depletion → skin friction ↓ → premature separation (GIS)
- Delay in the formation of instabilities in free shear layers
- Damping of the growth of instabilities though advection of RANS viscosity

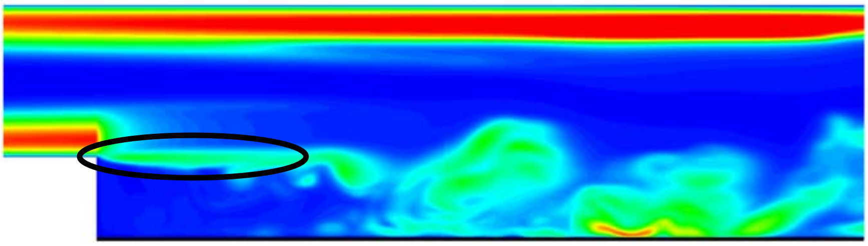
Solutions against GIS: Delayed Detached Eddy Simulation

- Ref. DDES: P.R. Spalart, S.Deck, M.L. Shur, K.D. Squires, M.K. Strelets, A. Travin. TCFD, vol 20 ,2006
- modification of the length scale $\tilde{d} = d_w - f_d \max(0., d_w - C_{DES}\Delta)$

$$\begin{array}{|ll} f_d = 1 & \tilde{d} = \min(d_w, C_{DES}\Delta) \\ f_d = 0 & \textit{RANS} \end{array}$$

- the model "refuses" LES mode, if it believes it is in a boundary layer

but can delay too much the switch into LES mode



ν_t field

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ZDES

- ZDES differs from DES97/DDES: hybrid & subgrid length scales, treatment of the near wall functions.
- Let us consider a multi-domain mesh made of N blocs and let *ides(ndom)*$_{1 \le ndom \le N}$ *be a label such as:*

$$\begin{array}{lcl} ides\,[ndom] & = & 0 \quad if\ domain\ ndom\ is\ in\ RANS\ mode \\ ides\,[ndom] & = & 1 \quad if\ domain\ ndom\ is\ in\ DES\ mode \end{array}$$

- The new ZDES length scale becomes:

$$\tilde{d}_{ZDES} = (1 - ides\,[ndom])\,.d_w + ides\,[ndom]\,.d_{DES}^{I\ or\ II} \qquad (*)$$

The hybrid length scale $d^{I,II}_{DES}$ is chosen depending on the problem of interest and **combines** "initial" version of ZDES (Deck, AIAA J., 2005) with the best features of DDES:

1. Separation onset fixed by the geometry : $\tilde{d}^{I}_{DES} = \min(d_w, C_{DES}\Delta)$
2. Separation on a smooth surface: $\tilde{d}^{II}_{DES} = d_w - f_d \max(0, d_w - C_{DES}\Delta)$

zonal definition of the subgrid length scale $\Delta = f(Vol^{1/3}, \Delta_{max}, f_d)$

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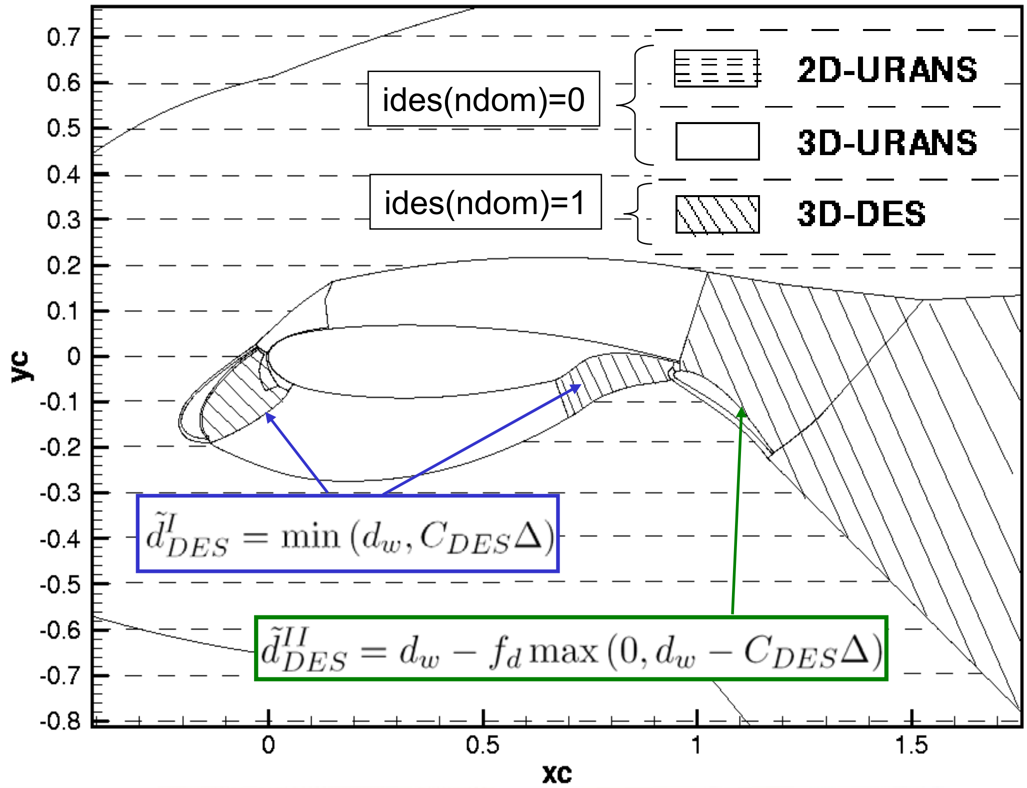
ZDES (cont'd)



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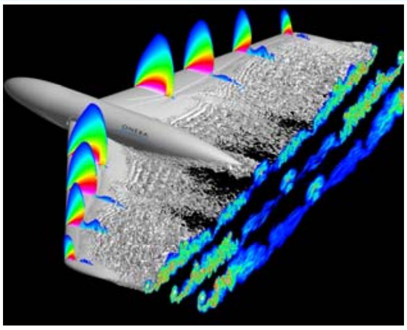
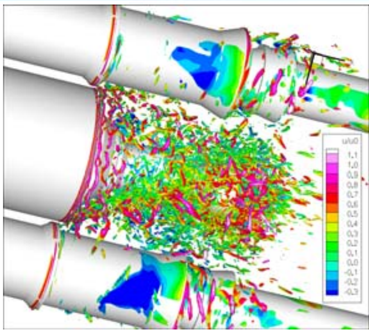
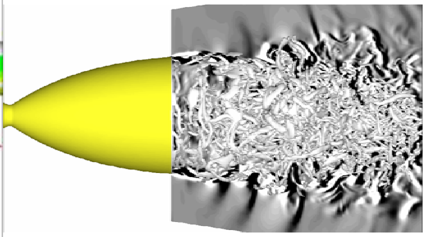
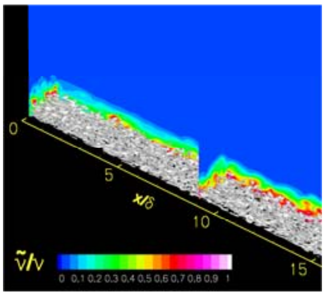
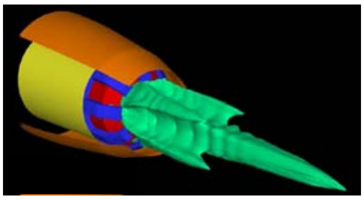
4. Applications











- Flow of category I: separation fixed by the geometry
- Flow of category II: separation fixed by a pressure gradient
- Flow of category III: include dynamics of the TBL

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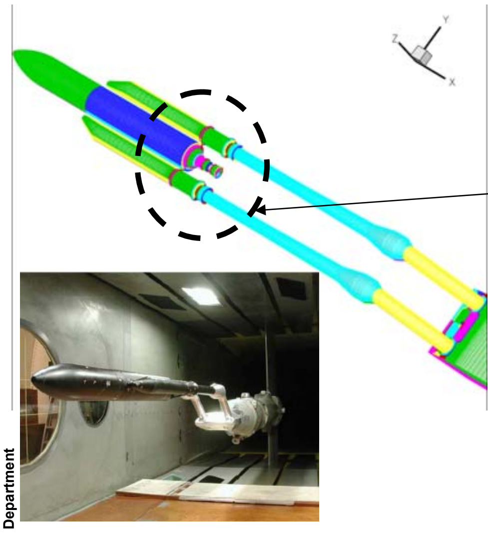
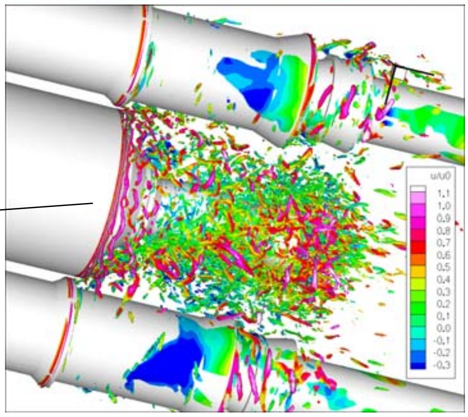
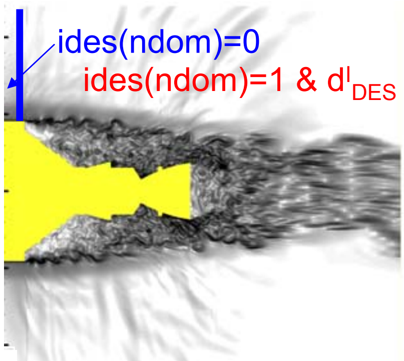
ZDES of transonic buffet loads on Ariane 5 launcher (flow of category I)







- 1:60 Ariane 5+ launcher model
- HSWT NLR wind tunnel. M=0.8
- N_{xyz}=22.10^6 -162 blocs

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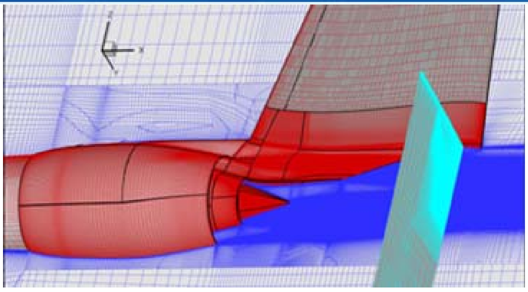
Second Symposium "Simulation of Wing and Nacelle Stall", June 22nd - 23rd, 2010, Braunschweig, Germany

Zonal-Detached Eddy Simulation of a Civil Aircraft Engine Jet Configuration (flow of category I & II)



Diameter of turbofan engines for civil transport aircraft ↑

➔ Engines are closer and closer to the wing

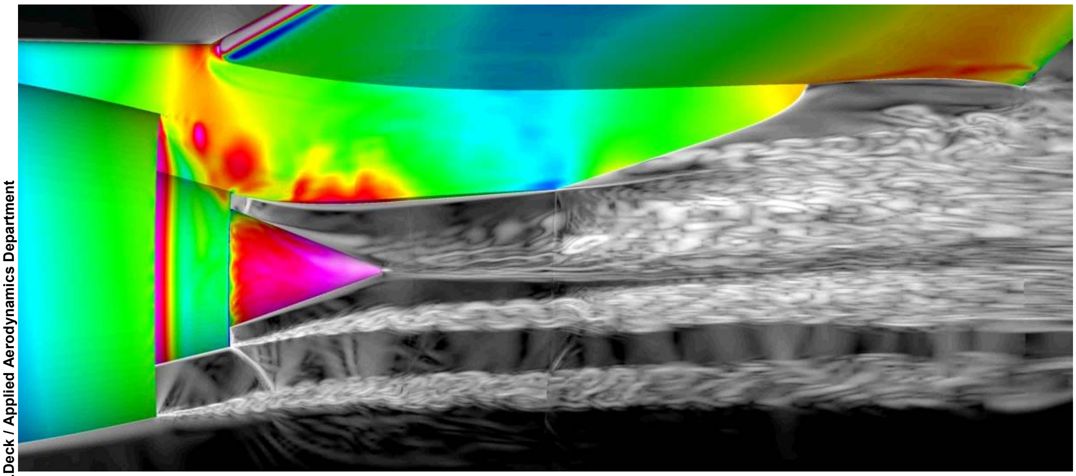
➔ Important/complex engine/wing interactions (mixing,…)

Experimental configuration (ONERA S3Ch WT)

➔ Wall to wall swept wing equipped with pylon/engine

➔ Nxyz=40.10^6 pts – 73 blocs - patch grid technique

➔ Both d^{I}_{DES} & d^{II}_{DES} may be used in the same calculation



elsA software

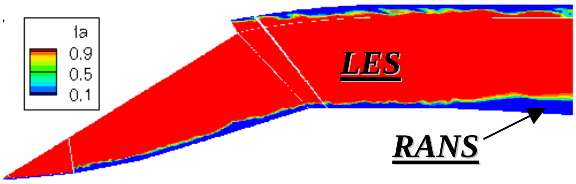
V. Brunet and S. Deck. 3rd Symposiun on hybrid RANS/LES, Gdansk, 2009)

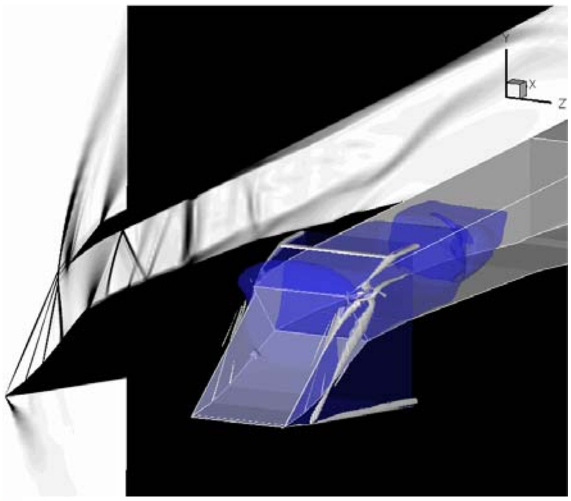
(V.Brunet, DAAP)

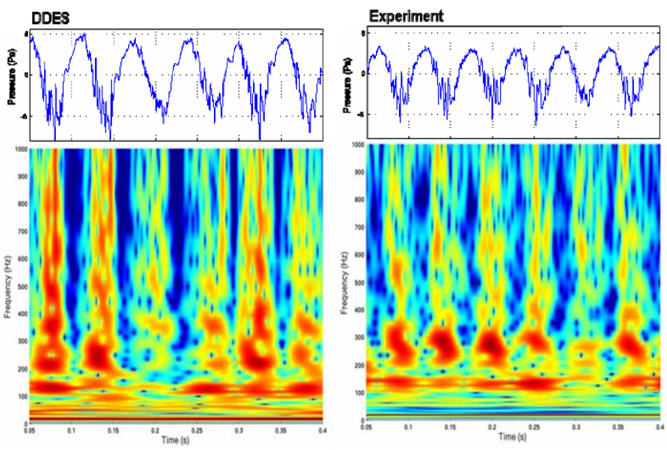
DDES of supersonic buzz in a rectangular mixed compression inlet (flow of category II)

Isolated inlet model – S3MA

- **high amplitude variation of the inlet mass flow and pressure**
- **can lead to thrust loss, engine surge, structural damage**
- **Nxyz=20.10^6. Re=29.10^6. M=1.8 (ONERA S3MA)**



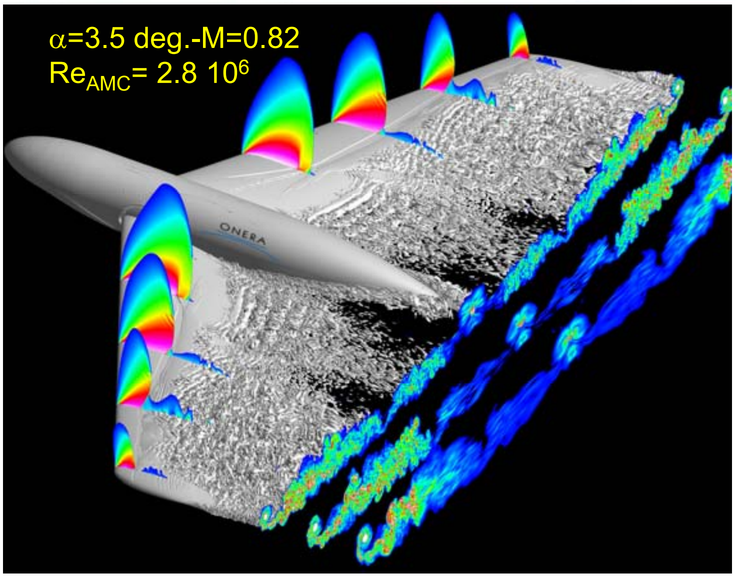




Wavelet transform

(Trapier et al., AIAA J., vol 46, No 1,2008)

ZDES of transonic buffet (flow of category II)



elsA software

- Wing body configuration (ONERA S3Ch)
- Nxyz=190.10^6 (patch grid technique)
- 1024 cores
- WT walls / wing deformation measured during test taken into account
- difficult case for hybrid RANS/LES
- both d^{I}_{DES} & d^{II}_{DES} are used in the same calculation
- buffet dynamics well simulated

(V.Brunet, DAAP)

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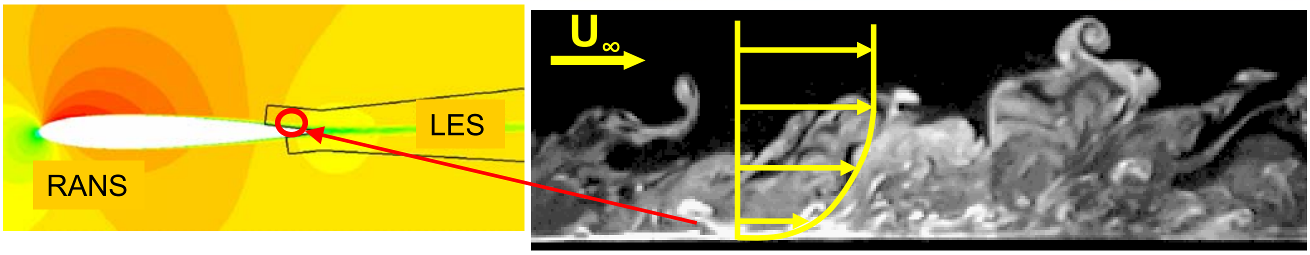
DISCUSSION. Wall turbulence simulation at High Reynolds number



- Natural use of "DES-type" methods: TBL treated in RANS mode

→ inappropriate in flows situations sensitized to the history of the upstream turbulence (flow of category III)

- RANS provides a solution that varies with a time-scale >> Δt

- LES solves small 3D structures

→ the inlet TBL has to account for these small eddies

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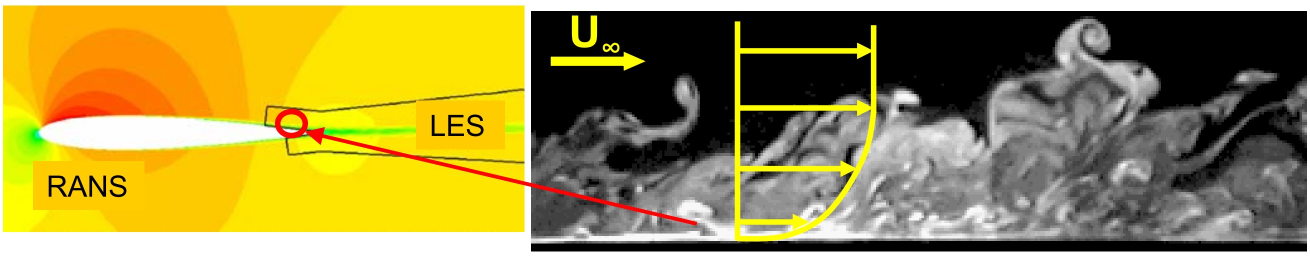
DISCUSSION. Wall turbulence simulation at High Reynolds number



DIFFICULTIES:

- Regenerate wall turbulence from only a statistical description !
- Prescription of a flowfield of the same nature as the one expected by the simulation

One has to specify an unsteady vortical flowfield that satisfies if possible :
• energy spectra
• 1st and 2^{nd} order statistics
• Phase correlation between the different modes: the most « tricky » since it describes the shape of the eddies, *i.e.* the intricate nature of turbulence

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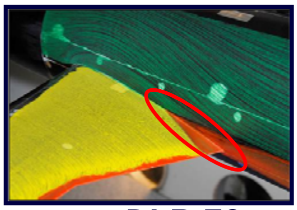
A critical example: junction flows. (flows of category III)

- A major and recurring issue (at the limit of the flight envelope)
  - Corner separation at junctions
  - Matters of concern : aircraft certification, drag, design stages
  - inability to anticipate corner separations in a reliable way

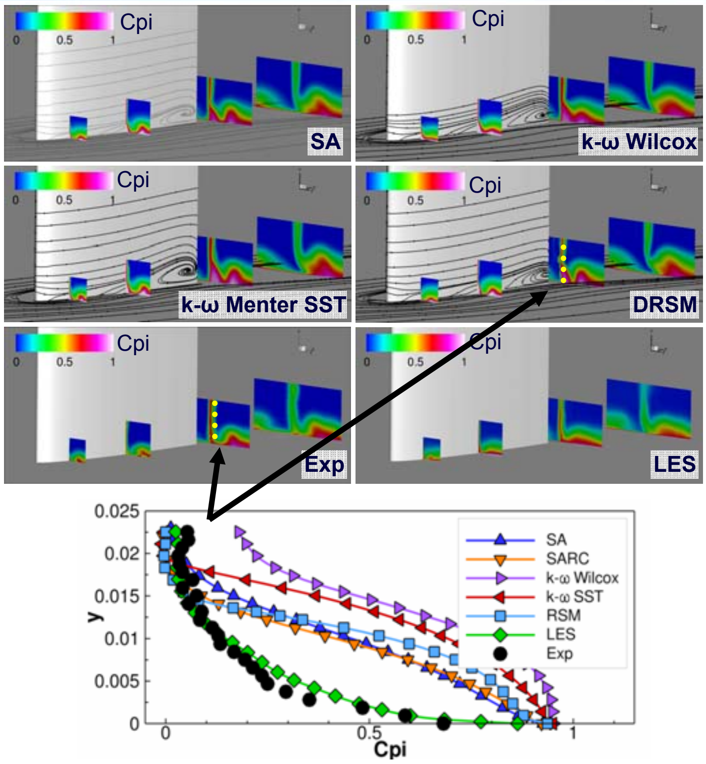
Key areas



DLR F6

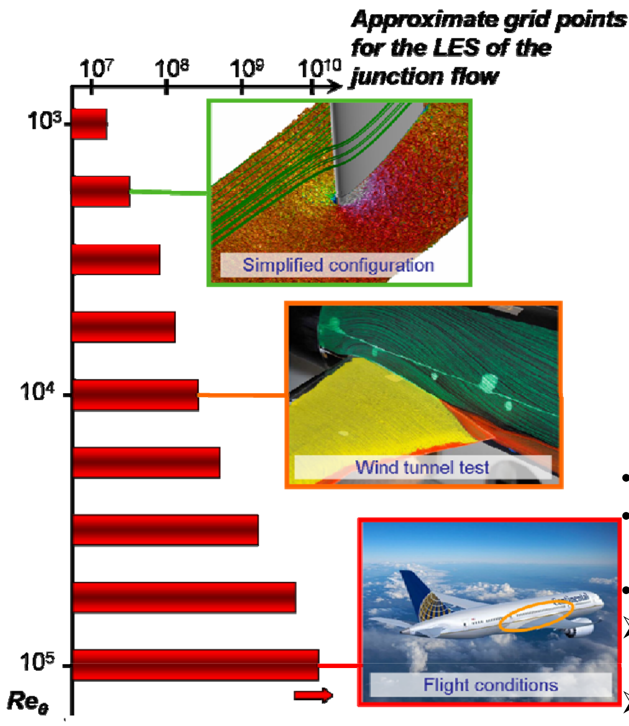
Numerical study of a junction flow. (flows of category III)

- Test case
  - Simplified wing/body junction
  - ONERA experiment
  - Re_θ=2100. Re_c=3.10^5 M=0.15.
- RANS
  - Consensus on corner flow separation
  - Low dependence on the model
- No experimental separation
- Mean flow well predicted by LES



(F.Gand, PhD, ONERA)

Towards Wall turbulence simulation at High Reynolds number. (flows of category III)



(F.Gand, PhD, ONERA)

Description of the present LES:

•Re_θ=2100. Re_c=3.10^5 M=0.15.
• Nxyz=65.10^6. Δt=0.5μs
• 8 NEC-SX8 cores.
•20000h CPU→80ms
• Synthetic Eddy Method (SEM) (Pamiès et al. Phys. of Fluids, 21, 2009, developed by ONERA)

• Re_θ =2100 very far from technical configurations
• "standard" (Δx^+ =50- Δz^+ =15-20) LES not reachable in a near future at realistic Re
• Ongoing work at ONERA:
➢ broadening of the application area of ZDES by permitting the activation of LES inside the BL
➢ ZDES acts as WMLES

Conclusion

- Development of Hybrid RANS/LES methods is still (and for a long time) necessary

- Hybrid RANS/LES offers an already quite interesting domain of applications

→ Importance of user decision load : zonal or non-zonal treatment of turbulence
→ Non-zonal methods are more "user-friendly" BUT
→ Is a « black-box push button » method realistic/utopist ?
→ Zonal and non-zonal hybrid methods will both grow

- Next foreseen challenges in applied numerical aerodynamics:

→ capture of TBL dynamics (transition & pressure-gradient driven separation)
→ capability to handle accurately complex configurations with validated unsteady tools
→ account for uncertainties (definition of the models, data of different nature)
→requirement of adequate experimental data base which are still missing

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