An introduction to advanced turbulence modelling.

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THE FRENCH AEROSPACE LAB

return on innovation

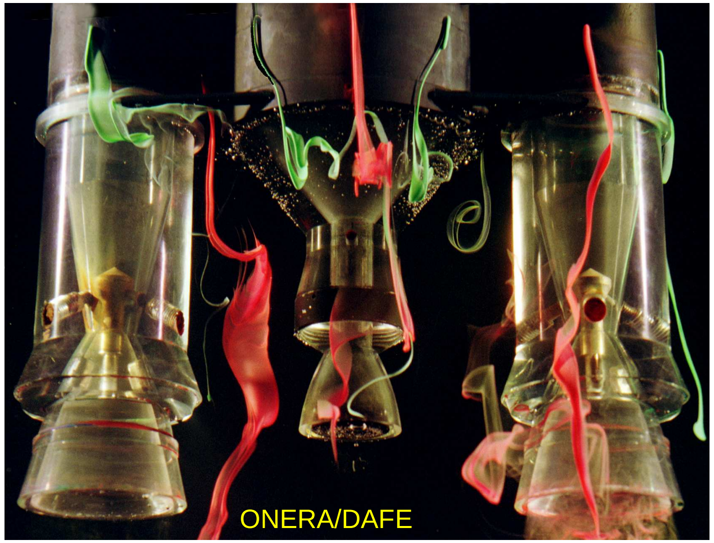
Paris XI –Turbulence

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…

→ Acoustic environment



→ dynamic loads

Direct Numerical Simulation

- 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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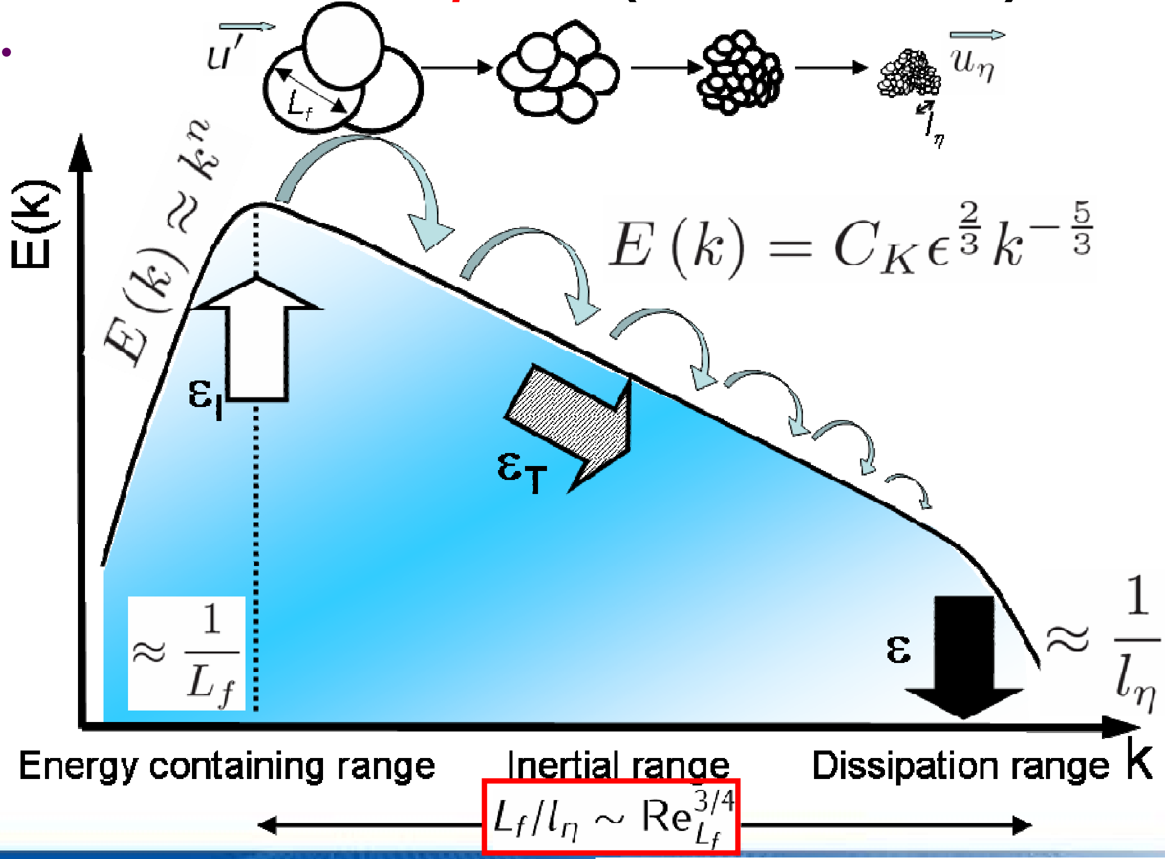

HIT TKE spectrum

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

(*adapted from Sagaut, Deck, Terracol, 2006)*

Direct Numerical Simulation. Cont'd

- DNS concept: "capture" all active scales

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

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

[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} z: spanwise direction
- $N_{xyz} > 10^{16}$ (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
- An introduction to massive calculation
- Applications

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

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*

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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'

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

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

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

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

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

Scale separation. Cont'd

- Reynolds tensor: $$\tau_{RANS} = \overline{\mathbf{u}' \otimes \mathbf{u}'}$$

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

- Subgrid Scale Tensor: $$\tau_{SGS} = \overline{\mathbf{u}' \otimes \mathbf{u}'} - \overline{\mathbf{u}'} \otimes \overline{\mathbf{u}'}$$

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

- Example:

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

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Scale separation. Cont'd

- LES : productions zones must be resolved

NB for LES:

In general, $$\overline{\overline{f}} = G \star G \star f \neq \overline{f} \qquad \overline{f'} = G \star (Id - G) \star f \neq 0$$

Most LES are performed in physical space (numerical schemes $\rightarrow$ additional dissipation)

⇩

The scheme acts as a numerical filter which damps the highest resolved frequencies

⇩

It is generally impossible to get access to the effective filter of the simulation

⇩

ILES, MILES …

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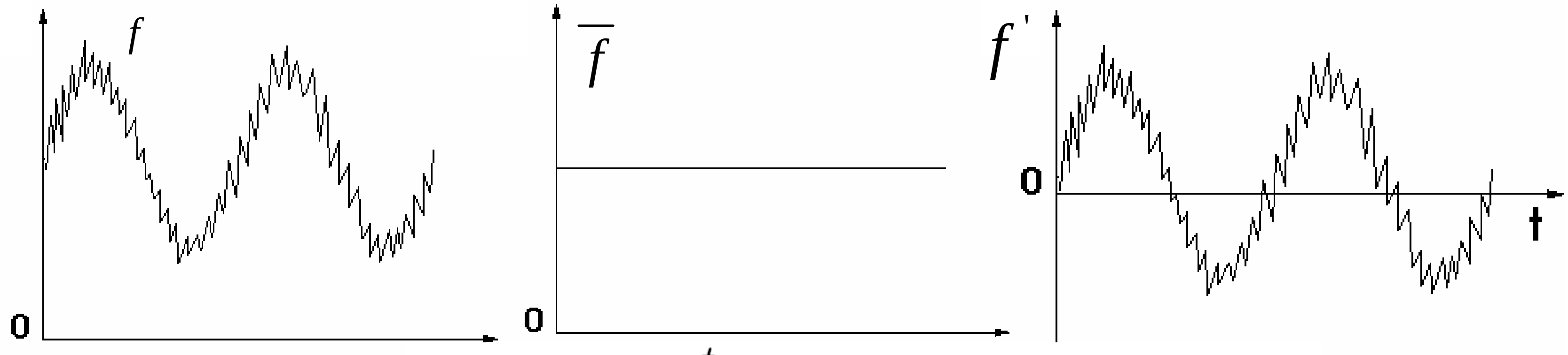
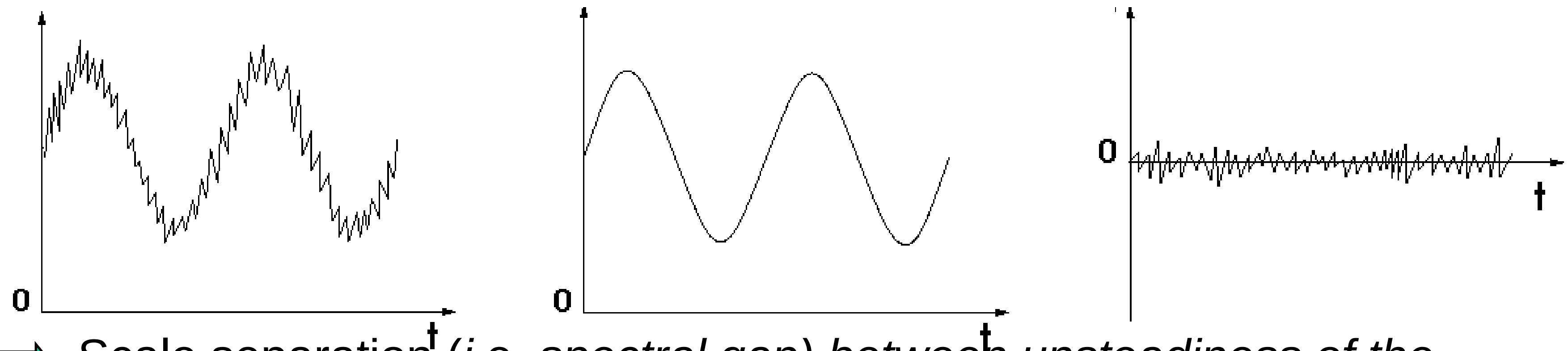
Unsteady statistical approach (URANS)

Reminder RANS: $\langle f \rangle_T = \lim_{T \to \infty} \frac{1}{T} \int_0^T f(s)ds$



Proposal URANS: f $\overline{f}(t) = \frac{1}{T} \int_{t-T}^{t} f(s)ds \quad with \quad T \gg \tau$



➡ Scale separation (*i.e. spectral gap) between unsteadiness of the Mean field (time scale θ) / turbulence (time scale τ)*

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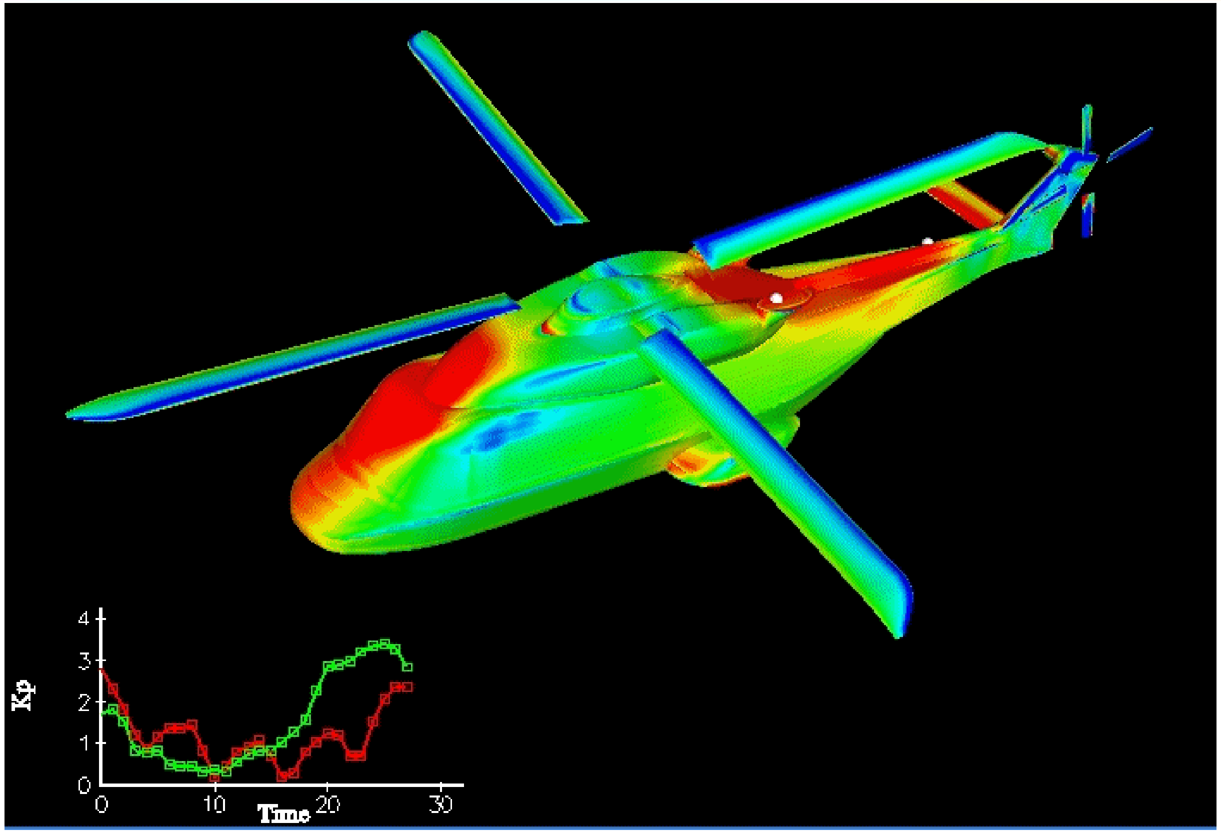
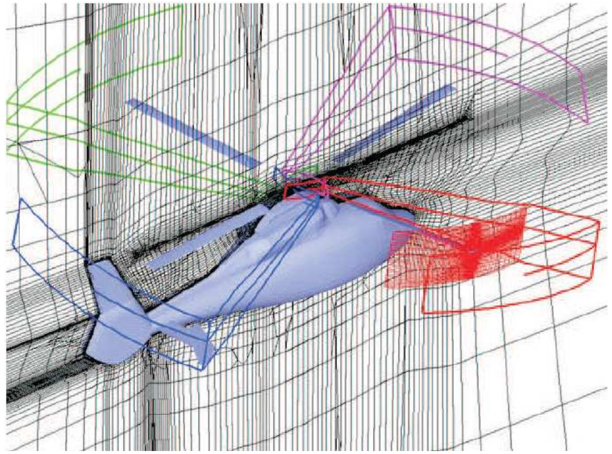
Unsteady statistical approach (URANS)





(T. Renaud, ONERA)

- URANS: turbulence model unchanged (here k-ω model)
- Chimera method (difficulty of the grid design)
- ALE method
- Boundary conditions

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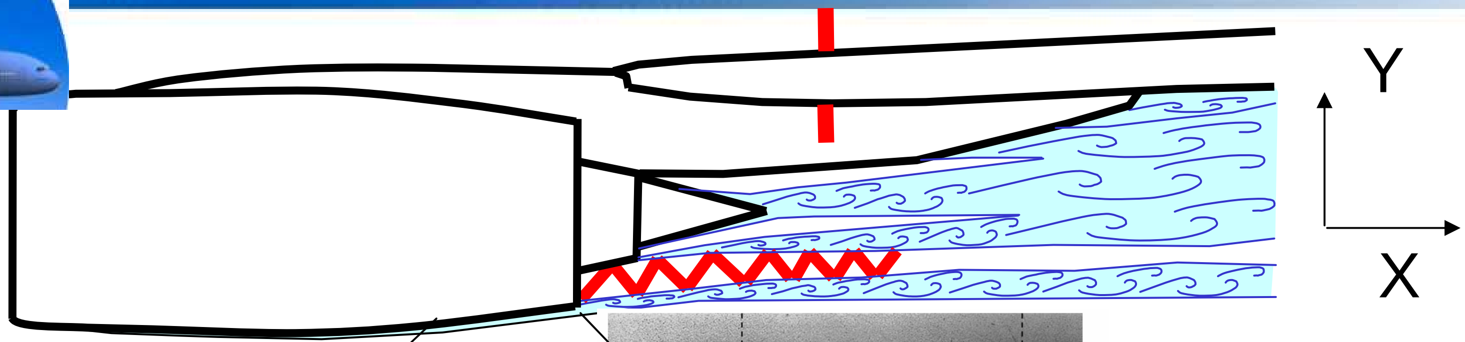
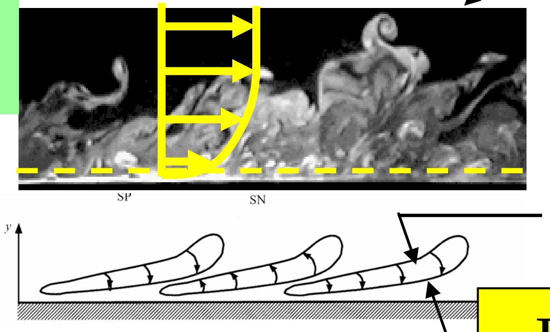
Turbulence modelling : the large scales. Production mechanisms.



M=0.8

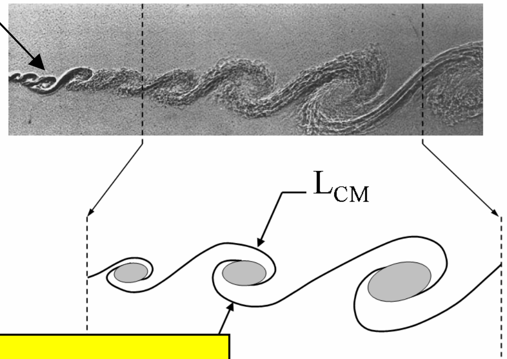
Boundary layer



Δx^{+}~50

Δy+~1

Δz+~15



Mixing layer

$\Delta x \sim \Delta z \sim \delta_{\omega}/2$

$\Delta y \sim \delta_{\omega}/20$

$L_{CL} << L_{CM}$

260 m/s

Lx=1m

0 m/s

1 u.p.=υ/u_{τ}=2.5µm

Boundary layer

RANS : Δx^{+}~500 Δy^{+}~1 Δz^{+}~1000 → 1.3 mm × 2.5µm × 2.6 mm

LES : Δx^{+}~50 Δy^{+}~1 Δz^{+}~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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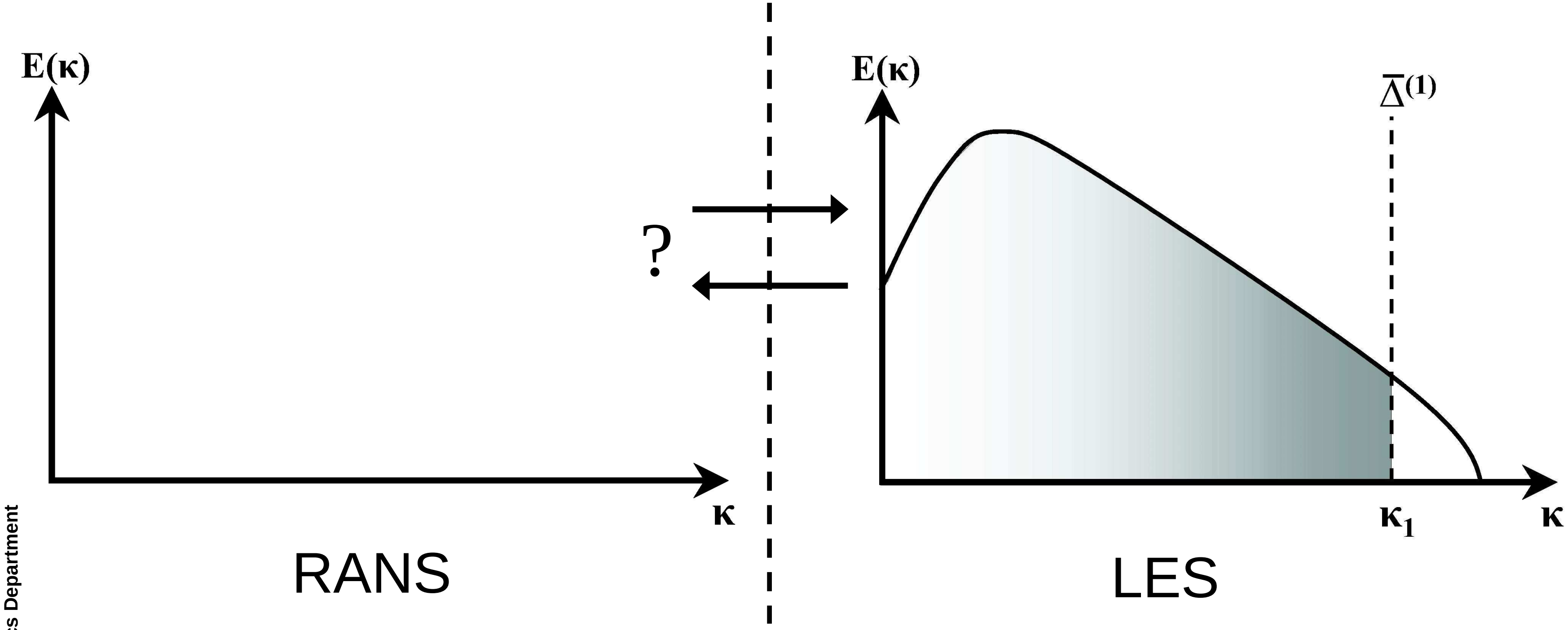
Rappels sur les opérateurs de séparation d'échelles (5/5)

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

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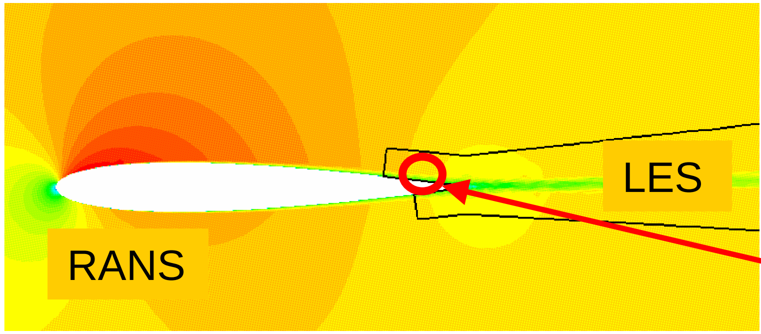
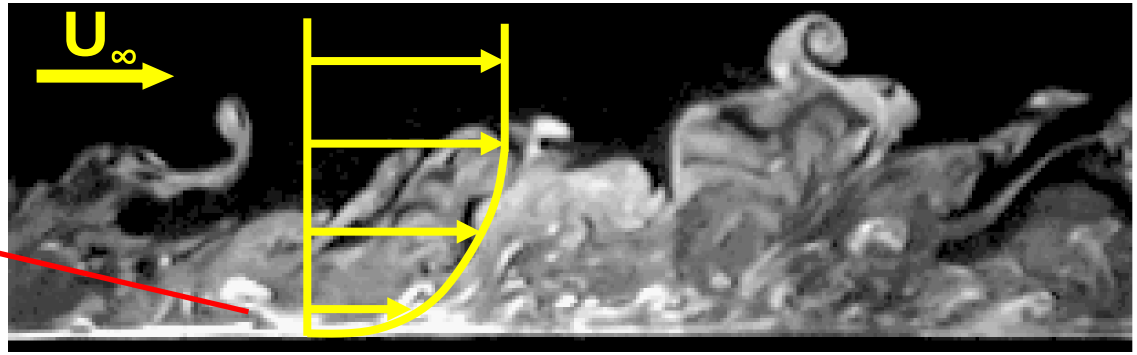
DISCUSSION. Wall turbulence simulation at High Reynolds number





- 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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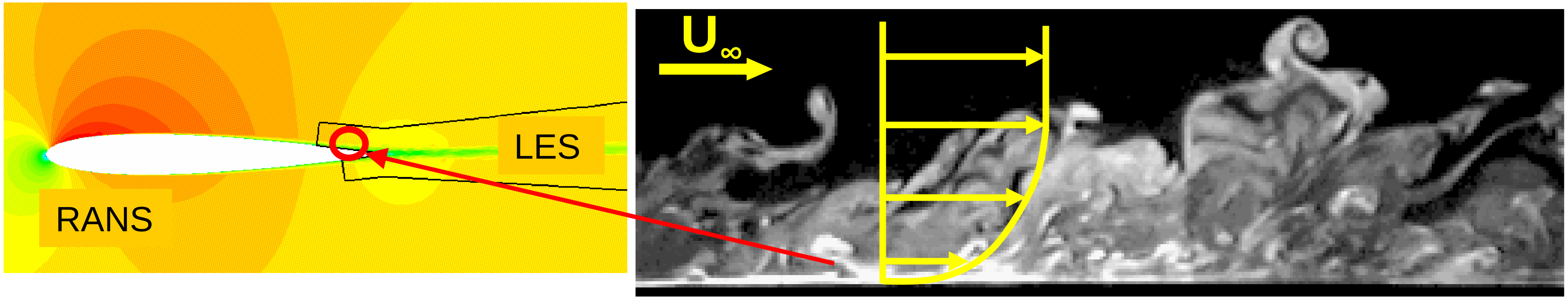
DISCUSSION. Wall turbulence simulation at High Reynolds number



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 2nd 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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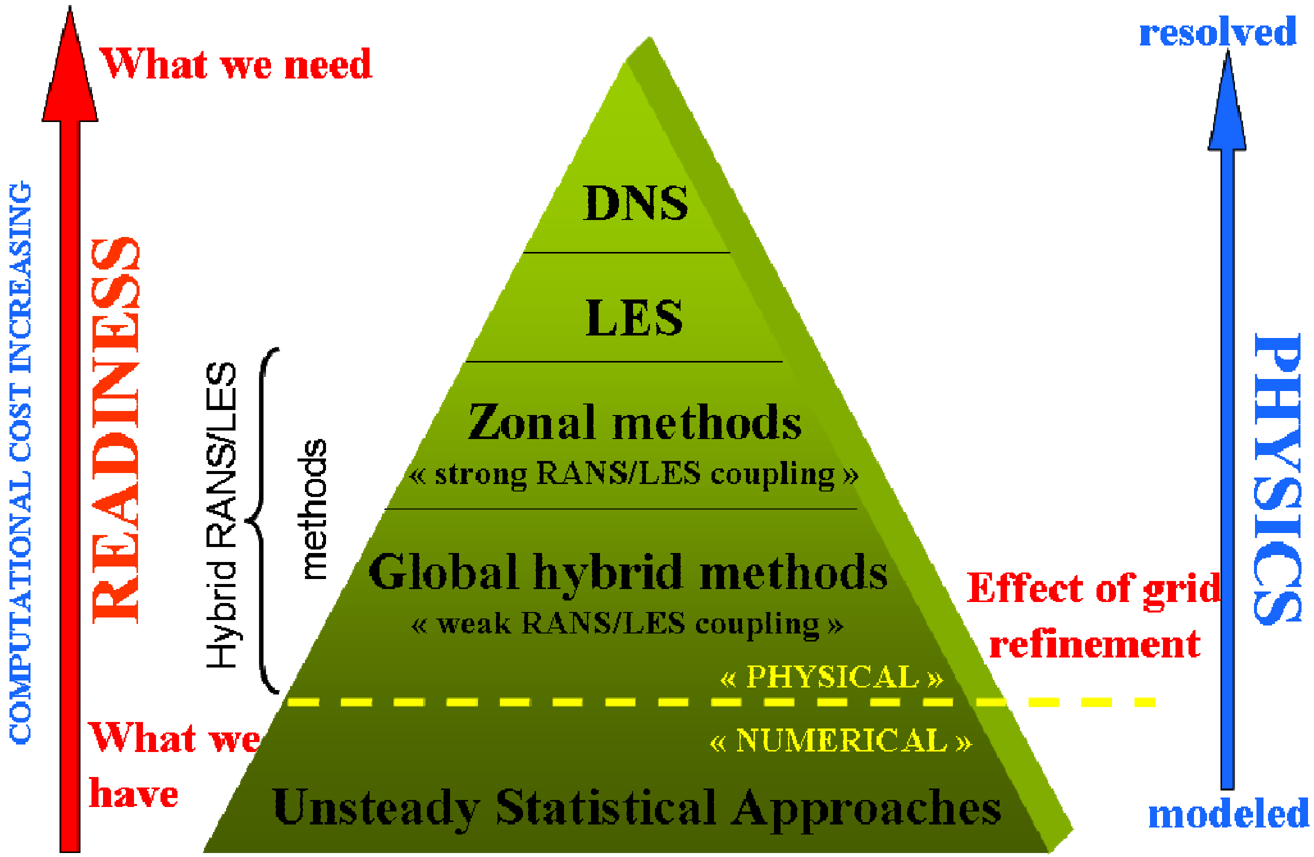
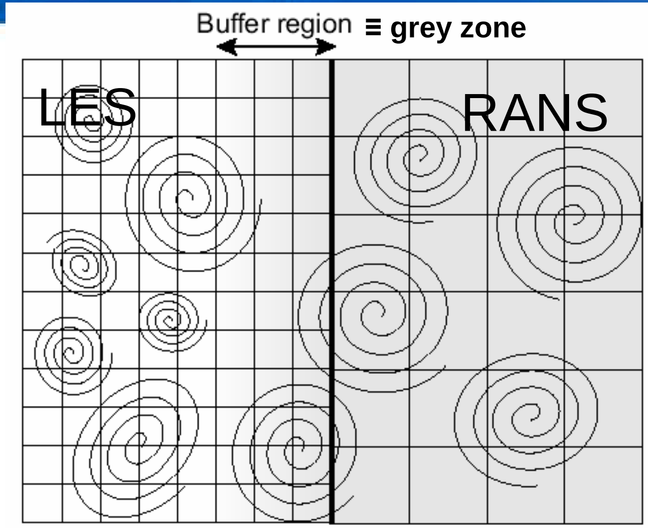
Classification of unsteady approaches

Modeling level ≡ Compromise solution (physics / CPU cost)

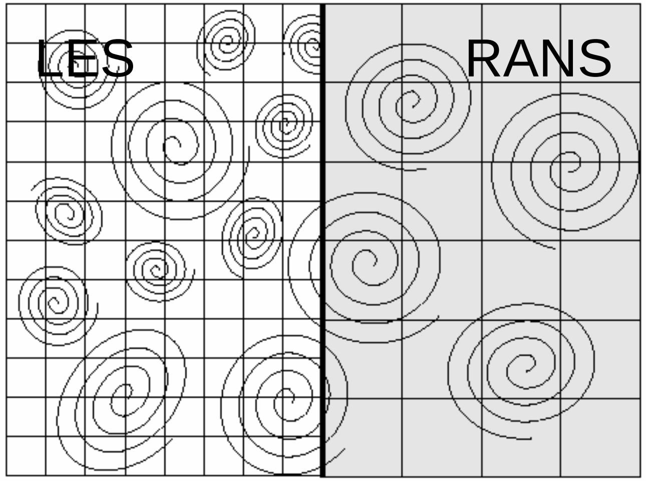


For a complete review, see *Sagaut P., Deck S., Terracol, M. (2006) Multiscale and Multiresolution approaches in turbulence. Imperial College Press, UK, 356 pp*

Global and Zonal RANS/LES approaches



Global methods *(Flow problems of cat I)*



Zonal methods *(Flow problems of cat II)*

CLASSIFICATION I: treatment of the RANS/LES interface

- 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

CLASSIFICATION II: problem of interest

- Cat I: massively separated flows (strong instabilities overwhelming inherited TBL turbulence)
- Cat II: flows sensitized to the history of the upstream turbulence

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Global and Zonal approaches (2) global hybrids : smooth transition

- Key idea: switch in eddy/subgrid viscosity
  - ⇨ Direct change in subgrid viscosity scaling
  - ⇨ Change in transport equations for turbulent quantities

- Common implementation
  - ⇨ Same number of variables
  - ⇨ 0-2 equations
  - ⇨ Massively separated flows (→ reduced buffer zone)

Examples of applications

Eddy viscosity scaling

$$\tau = \alpha . \tau^{RANS}$$

→ *Linear models*

$$\nu_t = \alpha \nu_t^{RANS} , \quad 0 \leq \alpha \leq 1$$

Speziale (1997) *(Very Large Eddy Simulation, VLES)*

$$\alpha = \left[1 - \exp\left(- \frac{\beta \Delta}{L_K} \right) \right]^n$$

Batten et al. (2000) *(Limited Numerical Scales, LNS)*

$$\alpha = \frac{\min\left[(LV)_{LES} , (LV)_{RANS} \right]}{(LV)_{RANS}} \rightarrow \alpha = \min\left\{ \frac{\nu_t^{LES}}{\nu_t^{RANS} + \eta} , 1 \right\}$$

Easy to implement…

Detached Eddy Simulation – Modelled Stress Depletion – Grid Induced Separation

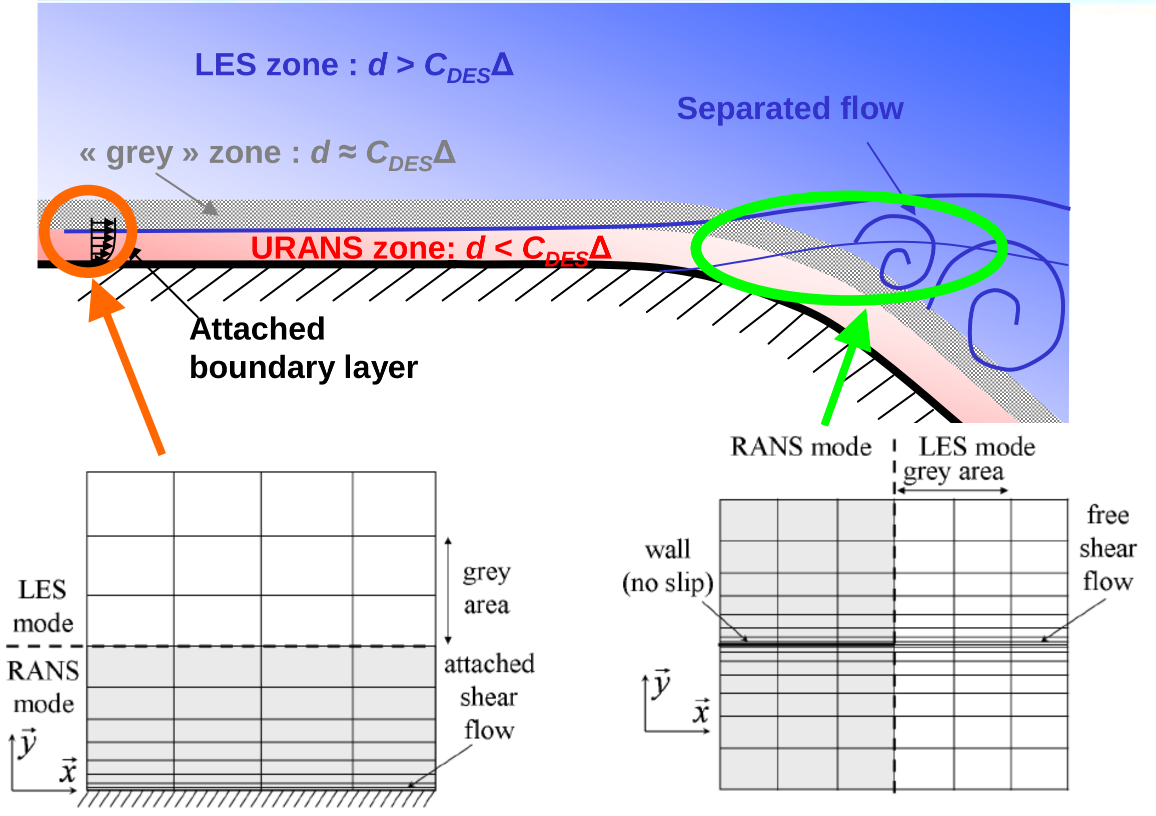
DES97 (Spalart et al. , 1997)

$$\tilde{\upsilon} \sim S\tilde{d}^2 \quad \tilde{d} = \max(d, C_{DES}\Delta) \quad \Delta = \max(\Delta_x, \Delta_y, \Delta_z)$$

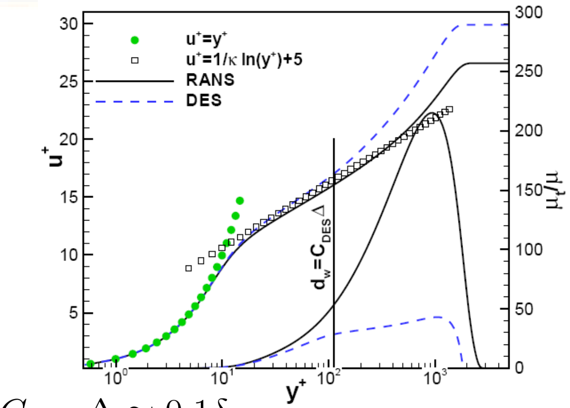
- natural use in thin boundary layers and in massive separation

- The needs of different flow regions places conflicting demands on the grid
  $\rightarrow \Delta_{tangential} > \delta$ requirement may be easily violated in industrial applications
  $\rightarrow$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)

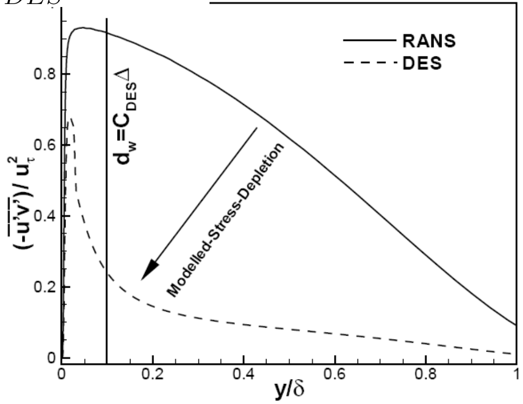
Detached Eddy Simulation – Modelled Stress Depletion – Grid Induced Separation



(a) "transversely induced MSD" (b) "longitudinally induced MSD"



$C_{DES}\Delta \approx 0.1\delta$



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

4. Solutions against GIS: ZDES – DDES - SDES

ZDES (Deck, AIAA J., vol 43, No 11, 2005)

- the user selects individual RANS and LES domains (analogous to RANS/LES coupling)
- grid refinement focused on regions of interest without corrupting the BL properties
- Near-wall functions disabled, $\Delta=(\Delta x \Delta y \Delta z)^{1/3}$ or $\Delta=\Delta_\omega$
- switches very quickly to LES mode
- Well adapted when detachment occurs near sharp edges

DDES (Spalart et al. , TCFD, vol 20, 2006)

- modification of the length scale $\tilde{d} = d_w - f_d \max(0., d_w - C_{DES}\Delta)$ $f_d = 0 \rightarrow$ RANS
- the model “refuses” LES mode, if it believes it is in aboundary layer
- well adapted when separation location is not known *a priori*

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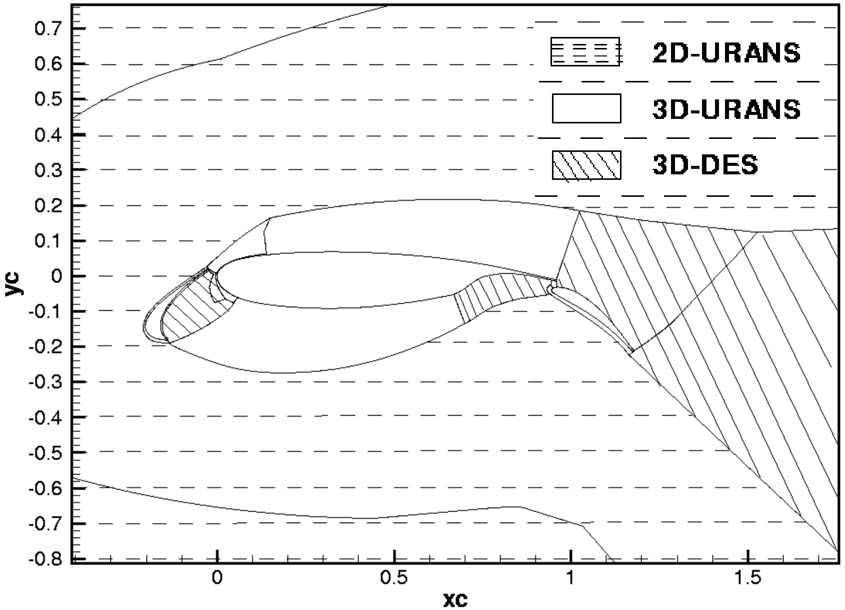
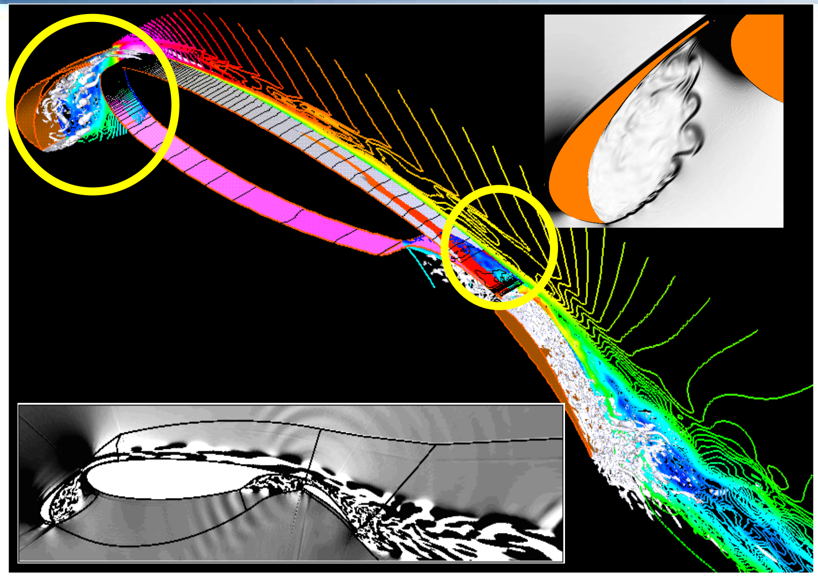
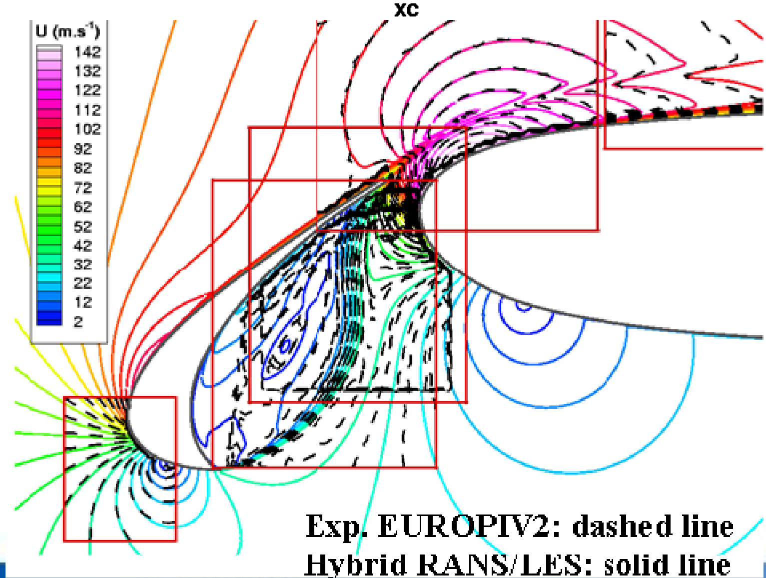
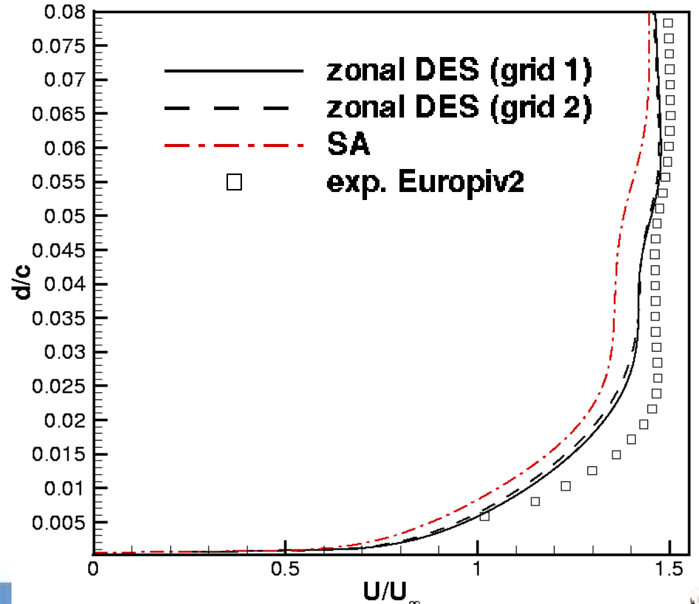
Zonal Detached Eddy Simulation (ZDES)









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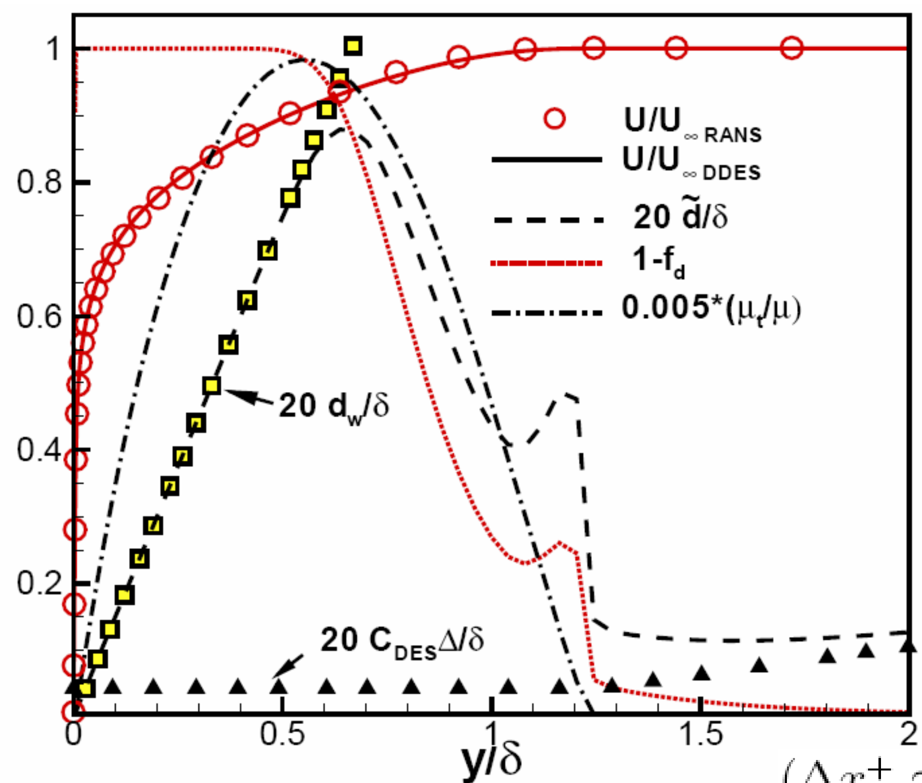
Delayed Detached Eddy Simulation (DDES)

- approche « automatique » capable de refuser le passage en mode LES
- collaboration Boeing / Univ. of Arizona / NTS / ONERA

$$\tilde{d} = d_w - f_d \max\left(0., d_w - C_{DES}\Delta\right)$$



$$f_d = 1 - \tanh\left(\left[8 r_d\right]^3\right)$$

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

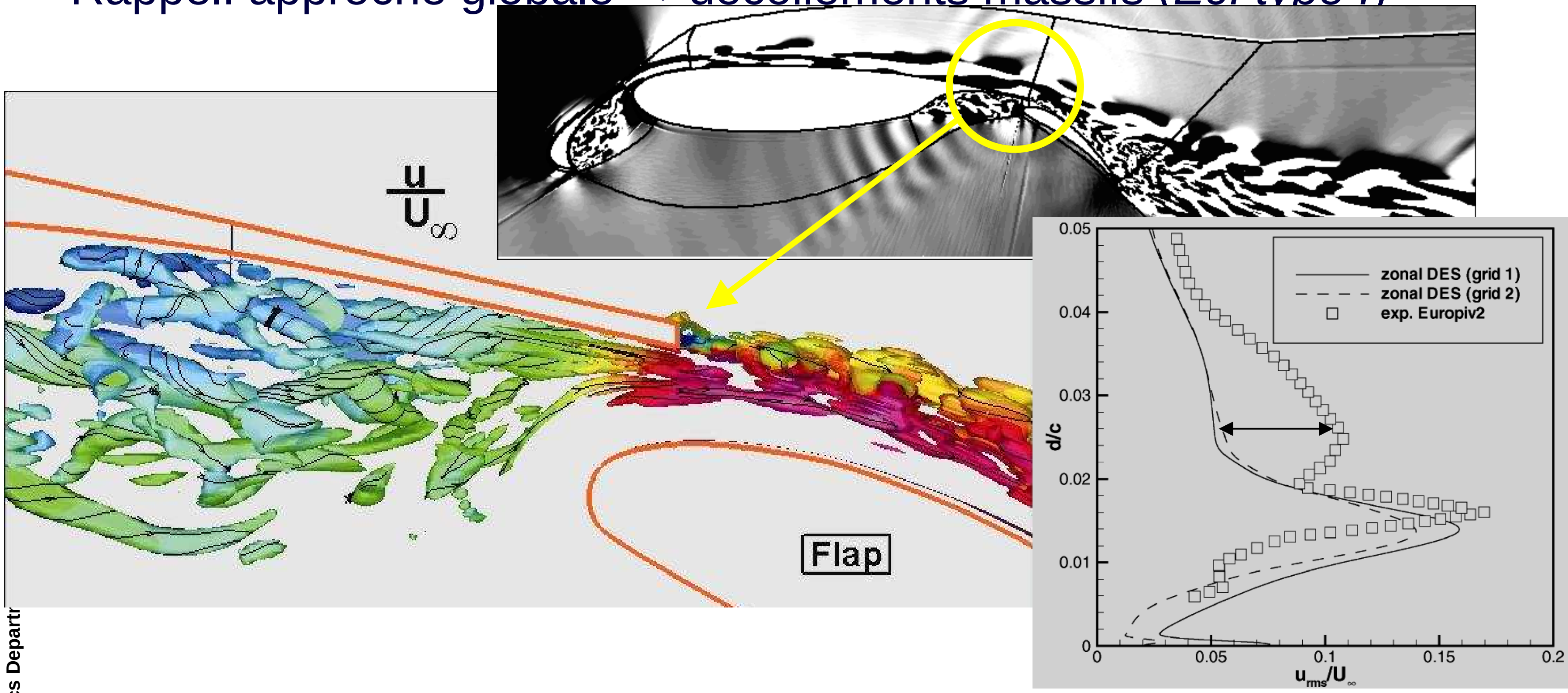
$$f_d = 1 \qquad \tilde{d} = \min(d_w, C_{DES}\Delta)$$

$$f_d = 0 \qquad \textit{RANS}$$

$(\Delta x^+ \approx 50, \Delta y^+ \approx 1, \Delta z^+ \approx 15)$

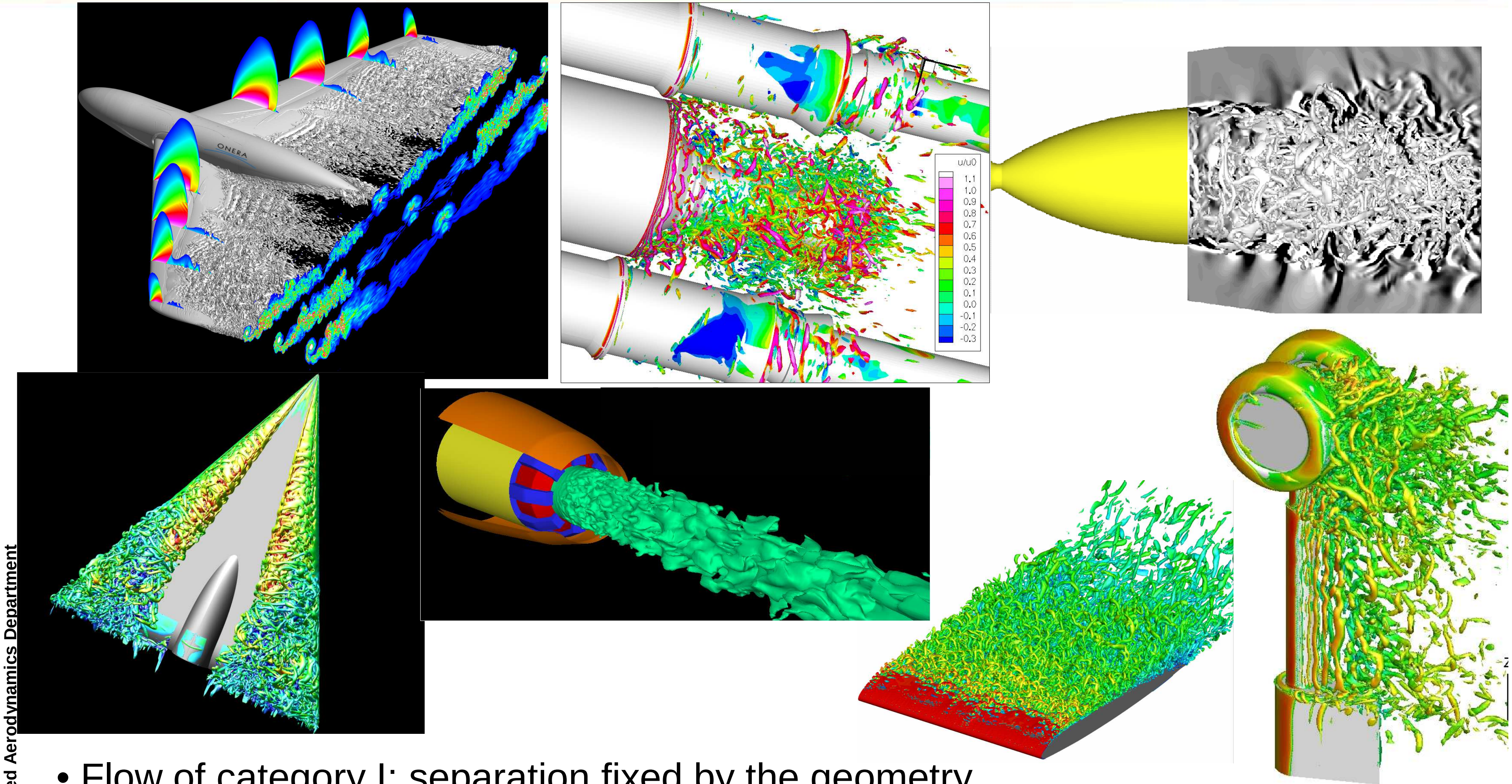
Stimulated Detached Eddy Simulation (SDES)

- Rappel: approche globale → décollements massifs (*Ec. type I*)



- Développement de conditions aux limites instationnaires en RANS/LES
- Turbulence pariétale → Utilisation « non-naturelle » des techniques de type DES
- Stimulated Detached Eddy Simulation (2006-2007 …)
- Traitement de $\tilde{\upsilon}$: remise à l'échelle et turbulence synthétique

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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Exploitation/Validation des calculs instationnaires

	Niveau de validation
1	**Efforts stationnaires** (portance, traînée, moment)
2	**Champ aérodynamique moyen** (profils de vitesse et de pression)
3	**Moments statistiques d'ordre 2** (rms, tensions croisées)
4	**Analyse spectrale en 1 point** (DSP)
5	**Analyse spectrale en 2 points** (spectres de cohérence et de phase)
6	**Ordre supérieur, temps-fréquence** (bi-cohérence, T. Ondelettes)

(adapté de Sagaut, Deck, Phil. Trans R. Soc A, 367, 2009)

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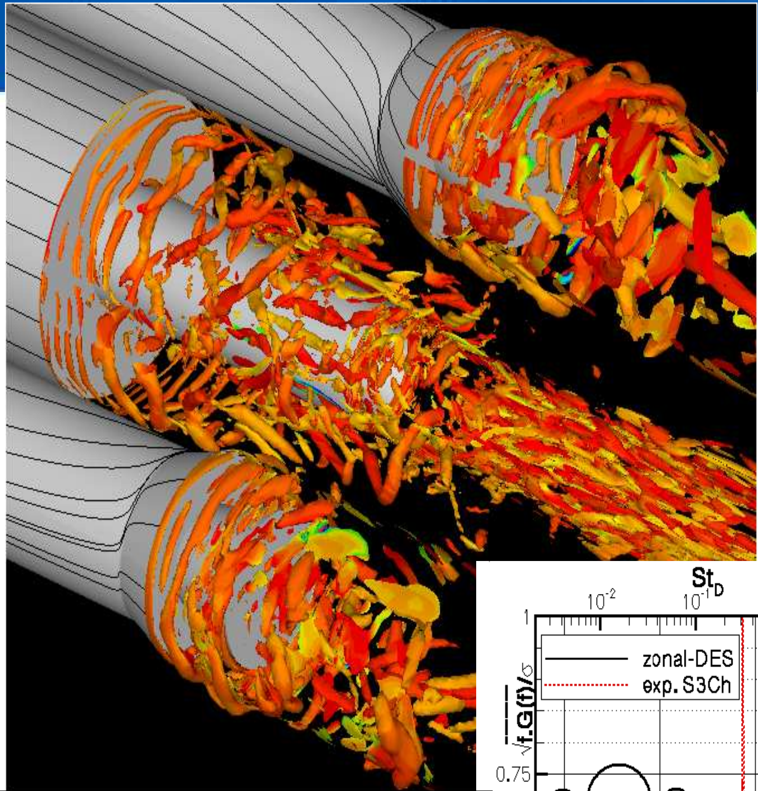
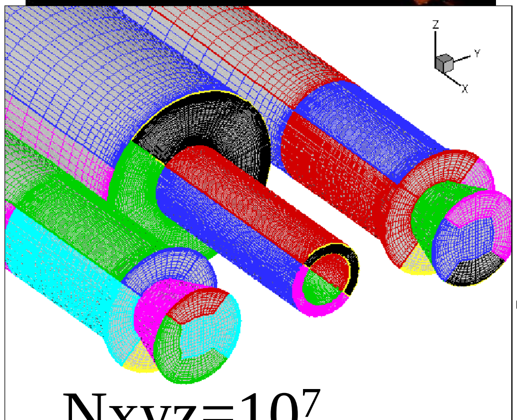
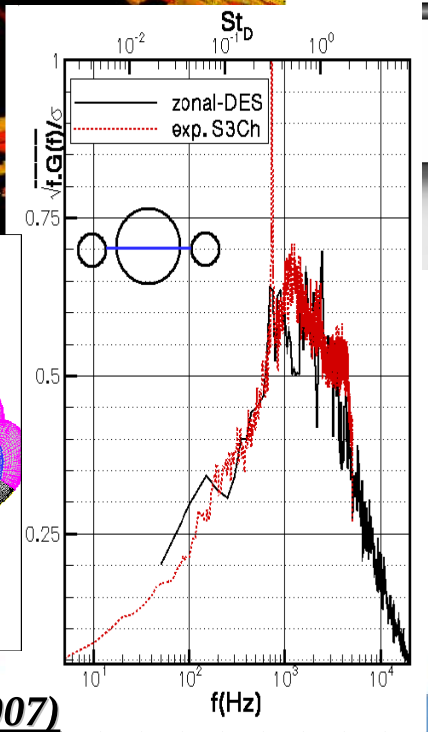
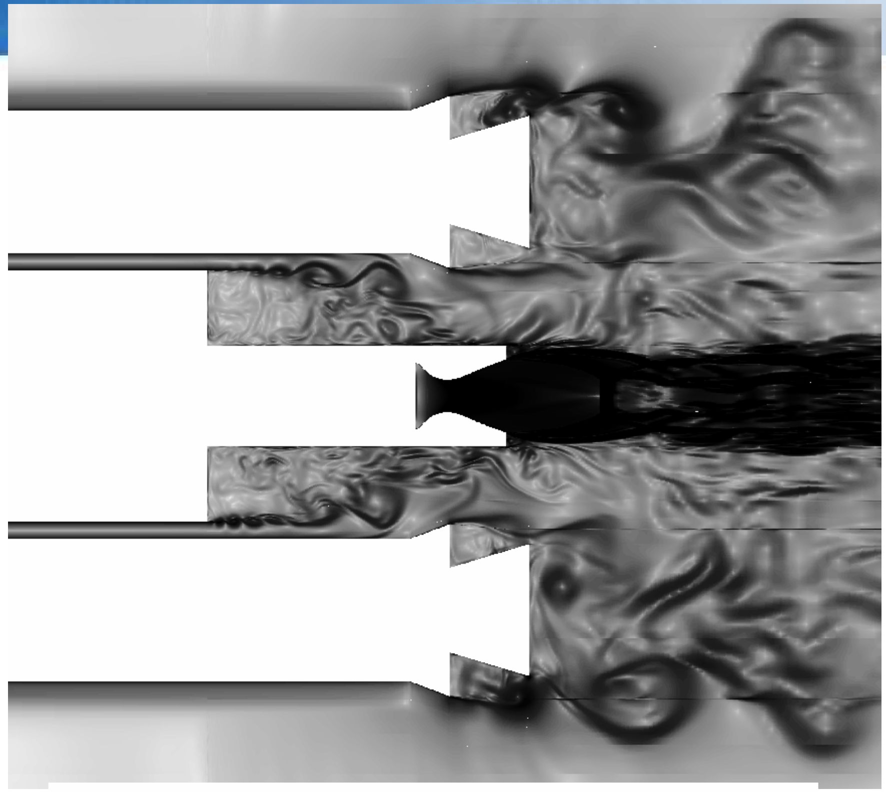
ZDES of launcher afterbody flows

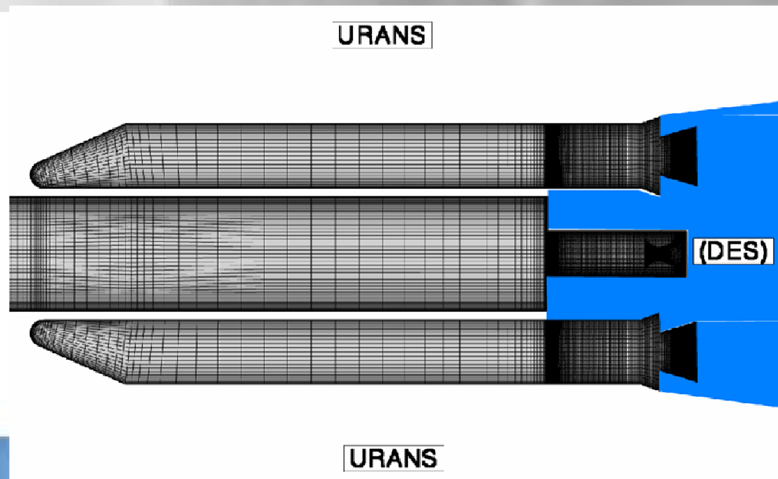




Nxyz=10^7







(Deck, Thépot, Thorigny 2007)

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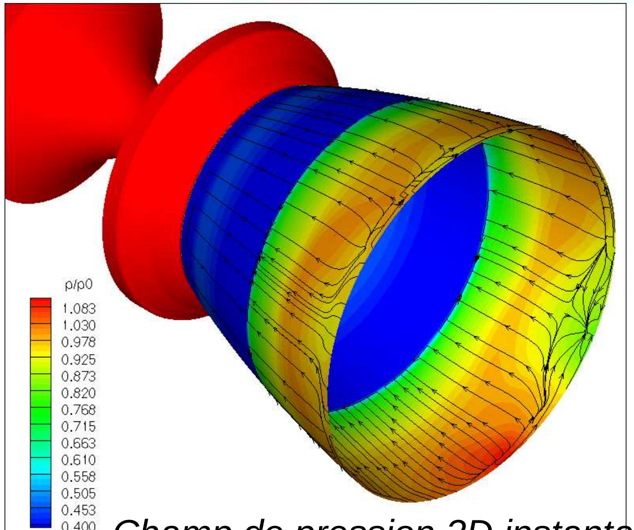
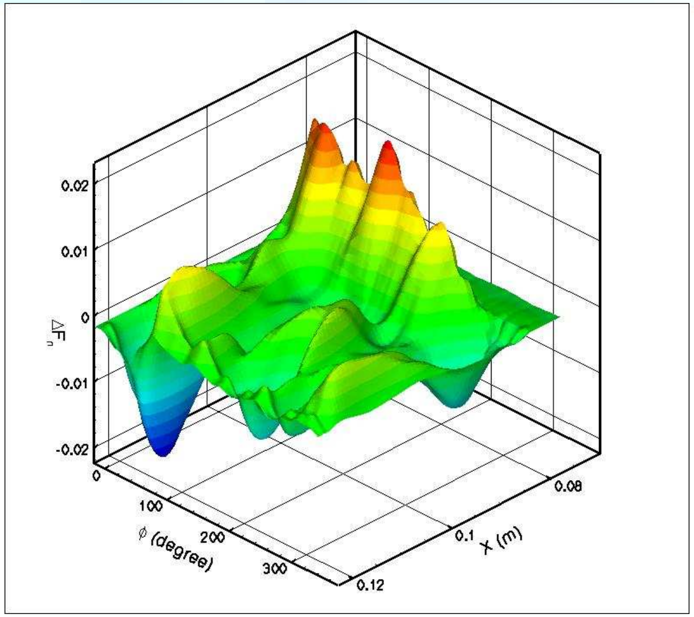
Tuyères type V2 : charges latérales

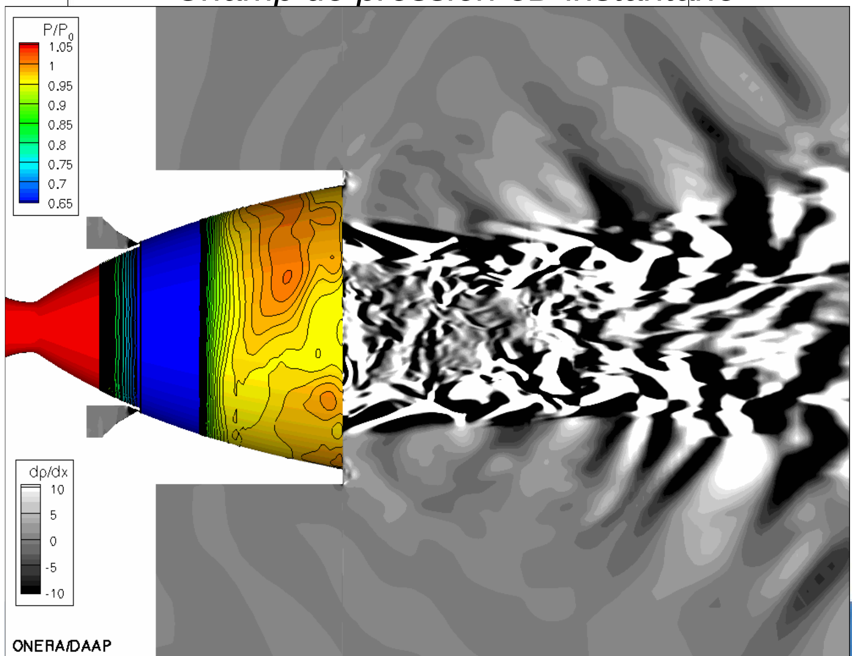


Champ de pression 3D instantané

- calcul DDES
- Nxyz=11.10^6



Distribution spatiale de l'effort instantané

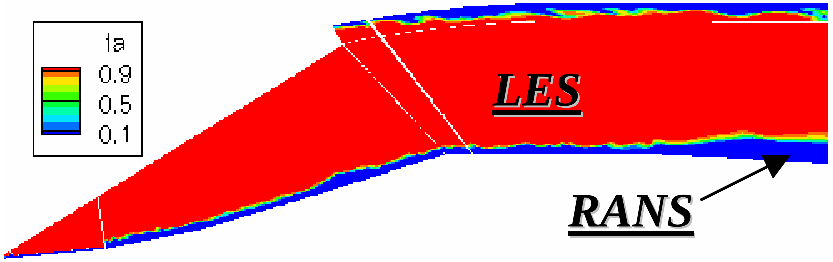


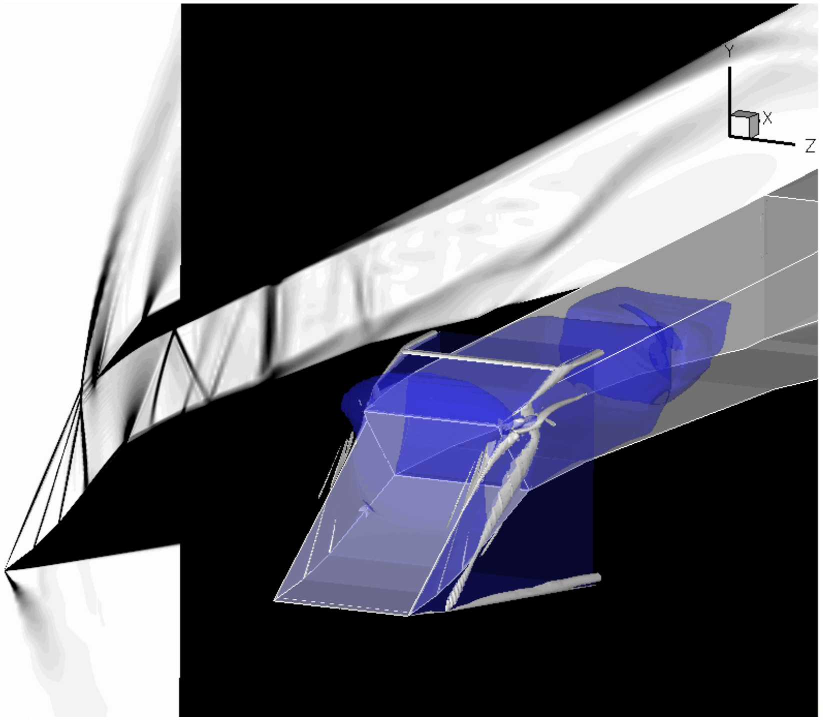
- CFD: effort aérodynamique pur
  (i.e pas de correction d'inertie)
- accès à l'ensemble du champ aérodynamique
- Asymétrie du recollement de lèvre
- Possible origine des Side-Loads
-

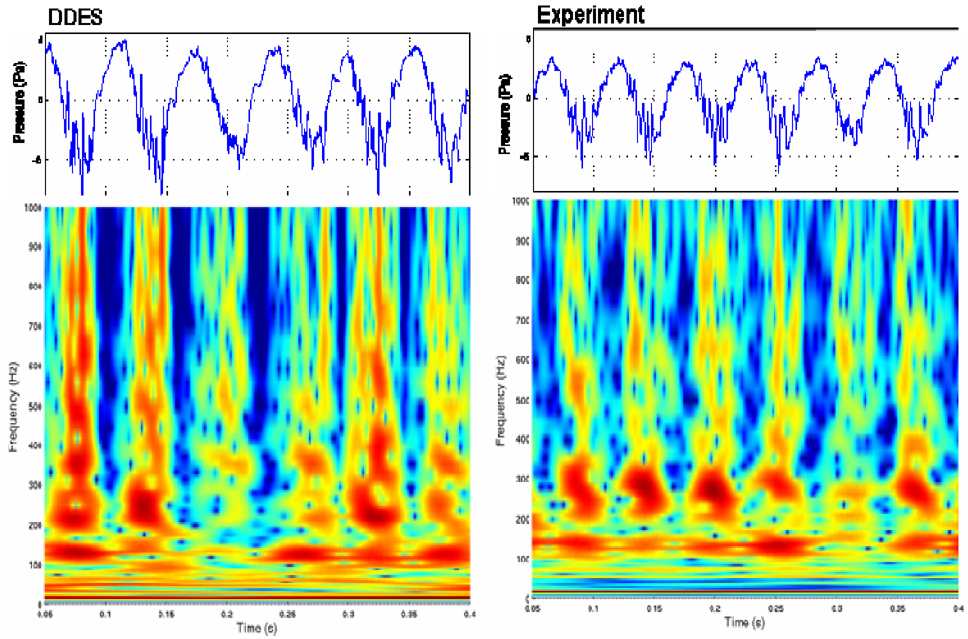
DDES of supersonic buzz in a rectangular mixed compression inlet

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)

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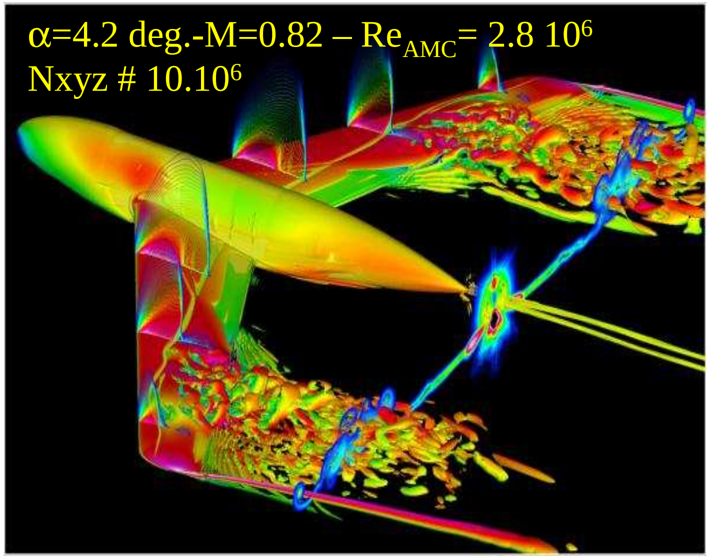
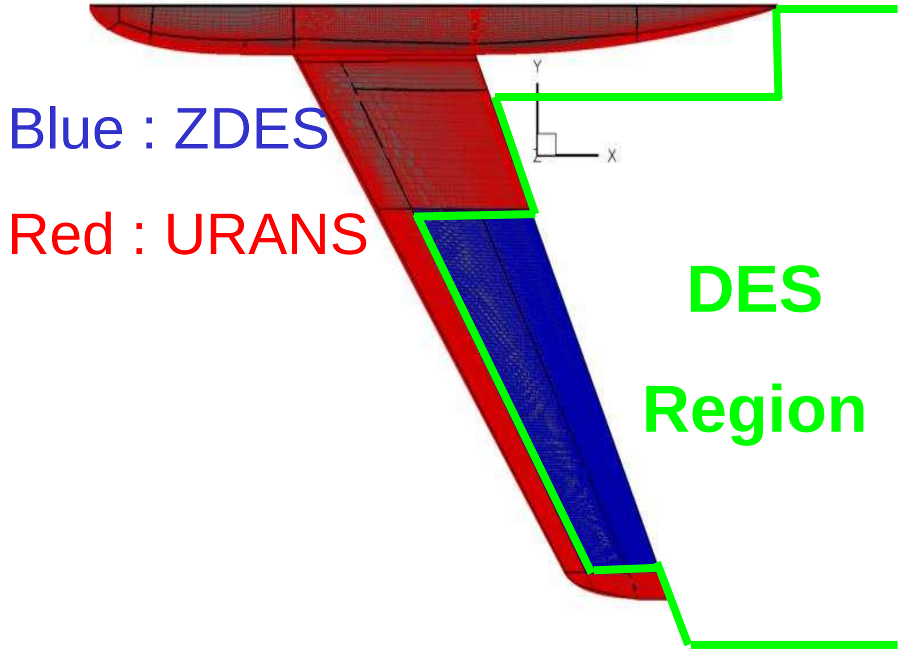
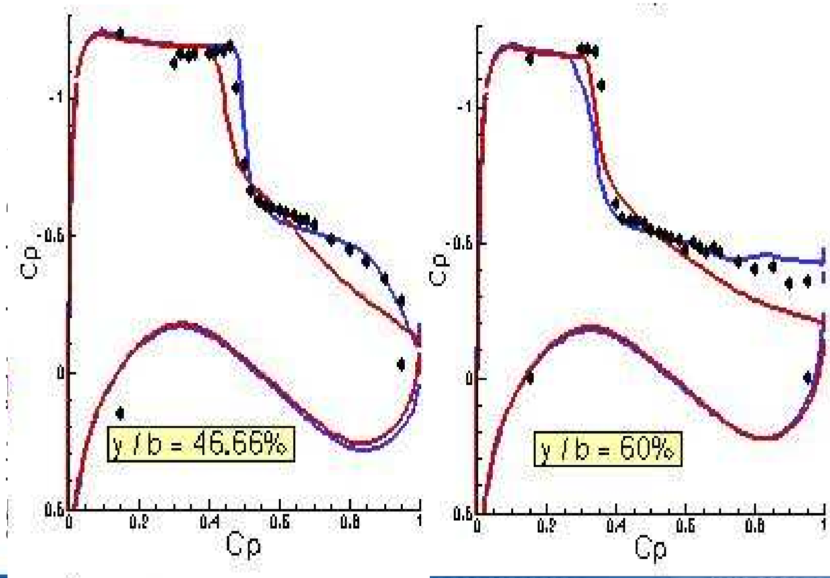
ONERA

ZDES of transonic buffet



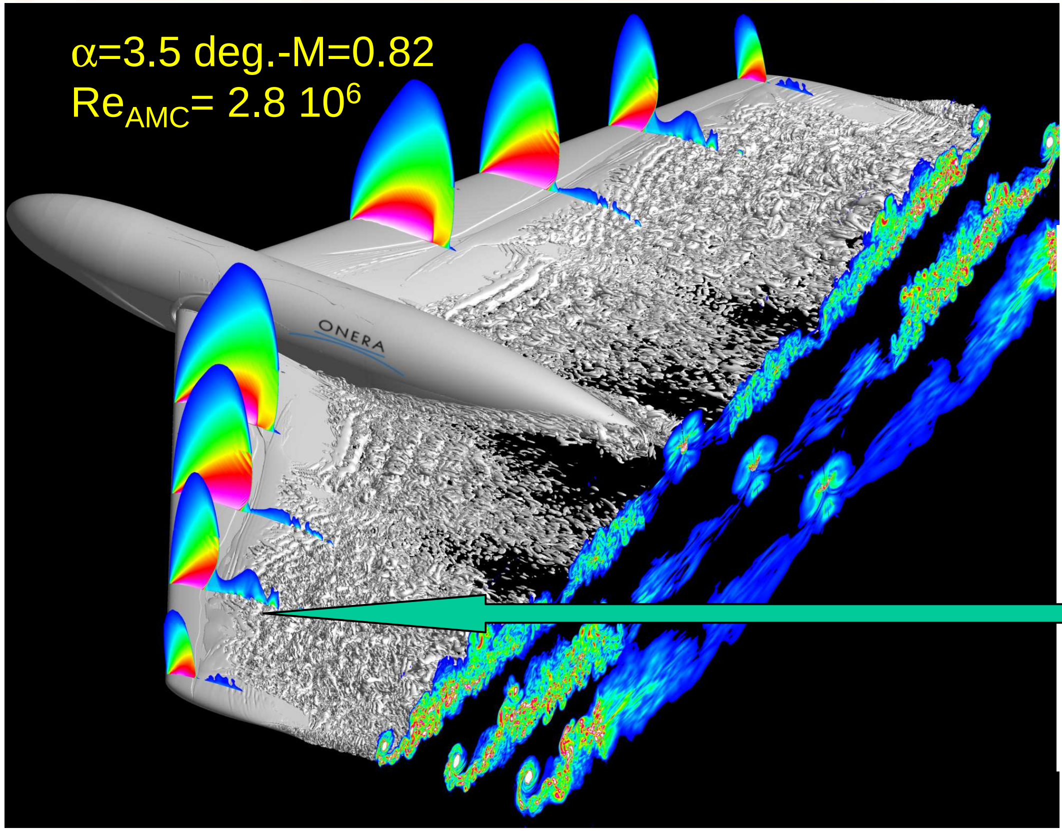


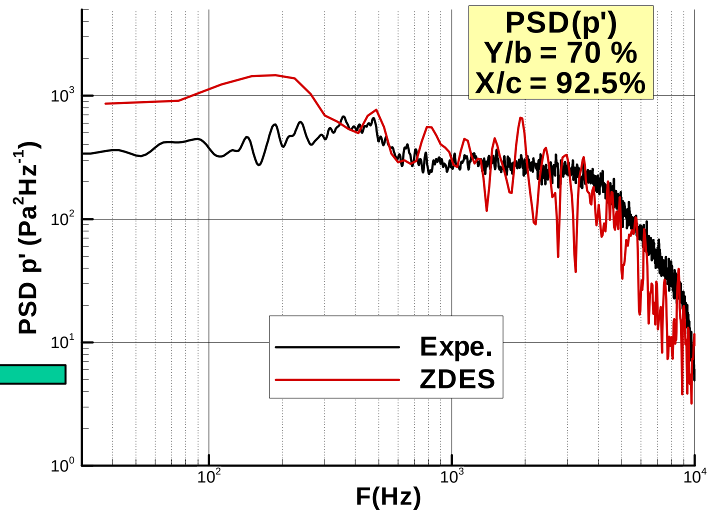


- Wing body configuration (ONERA S2MA)
- Nxyz=10.10^6. 84 blocks
- difficult case for hybrid RANS/LES
- intense separation / curved separation line
- steady solution with URANS
- separation underestimated by URANS
- mean shape of separated area well reproduced by ZDES

(Brunet, Deck, Corfou Symposium, Springer 2007)

ZDES of transonic buffet (flow of category II)





elsA software

- **Wing body configuration (ONERA S3Ch)**
- **Nxyz=190.10⁶ (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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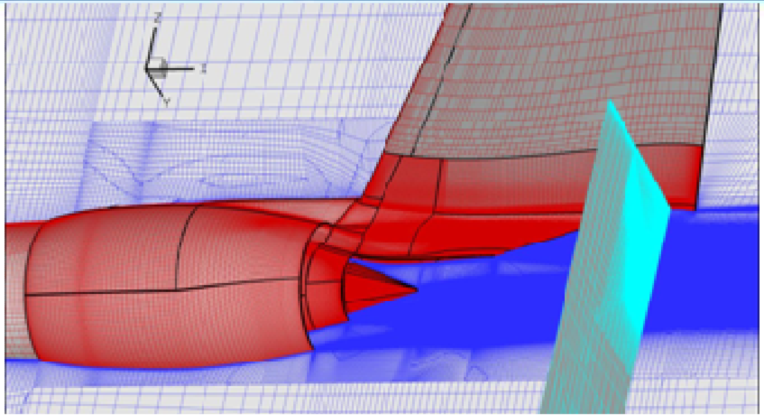
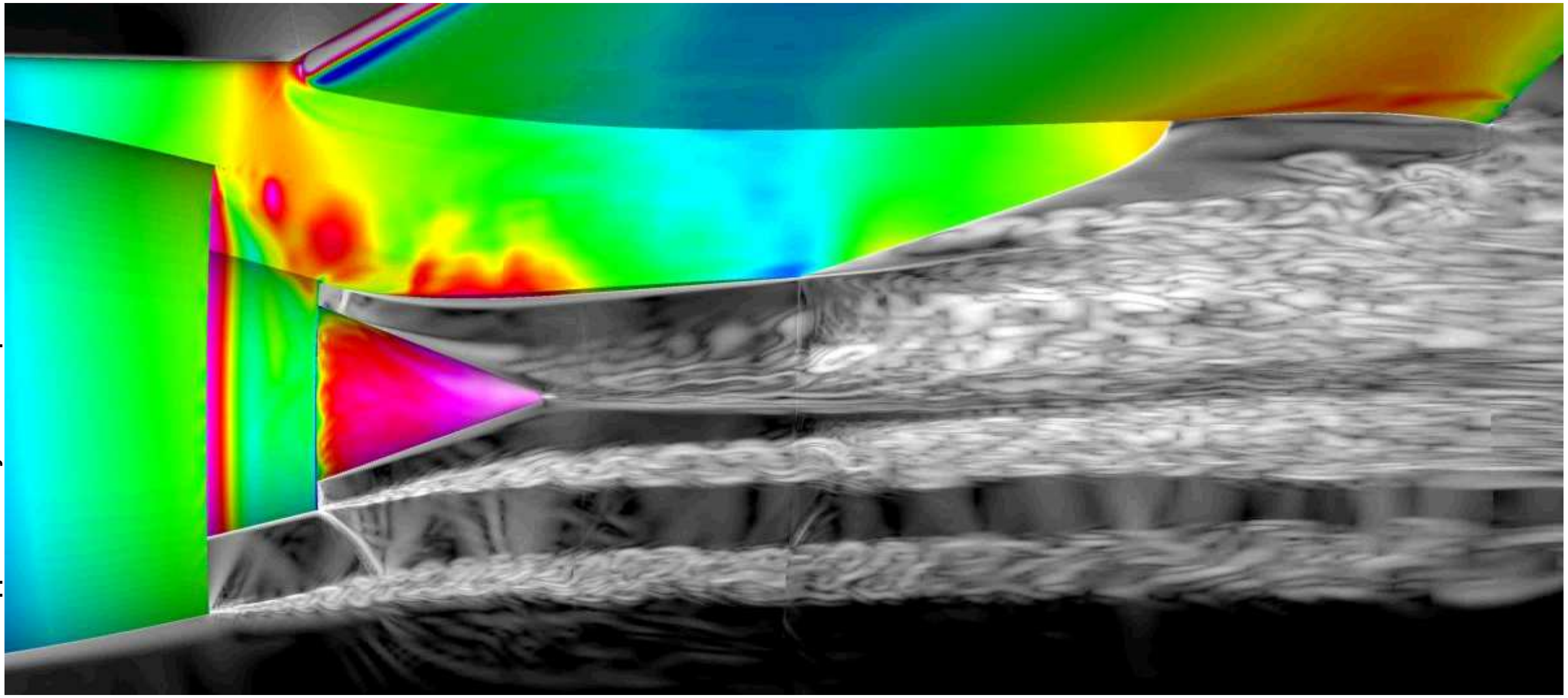
ZDES of a civil aircraft jet engine configuration



- prévision des mécanismes de mélange, thermique et acoustique
- approche ZDES (AIAA J., vol 43, No. 11, 2005)
- Nxyz=40.10^{6} pts – 73 blocs
- géométrie 3D / schémas numérique
- code industriel : ***elsA***



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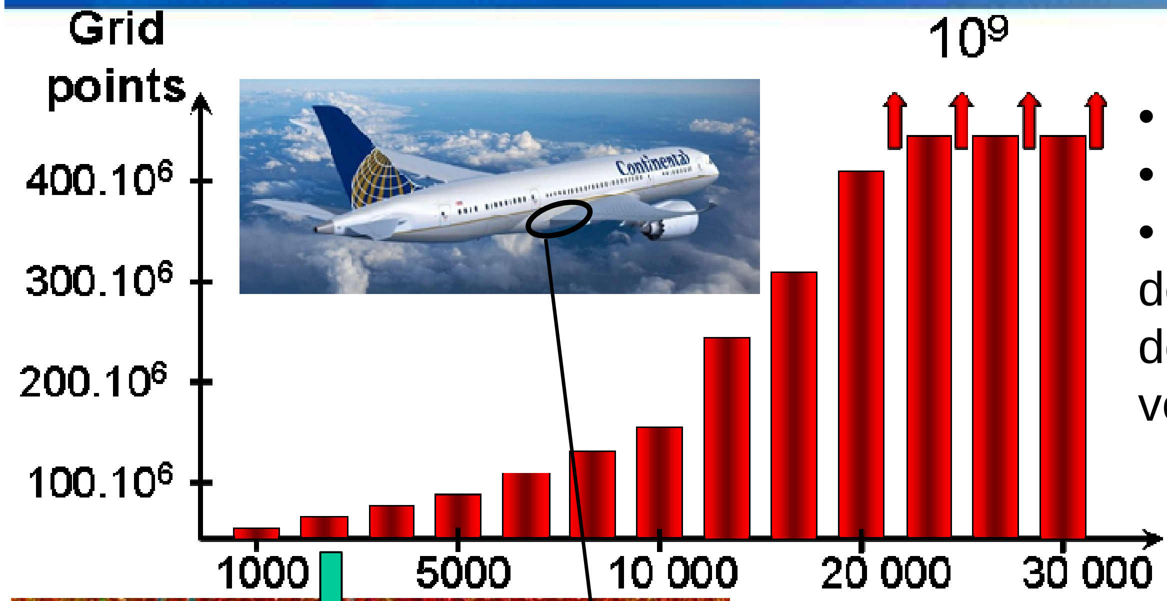
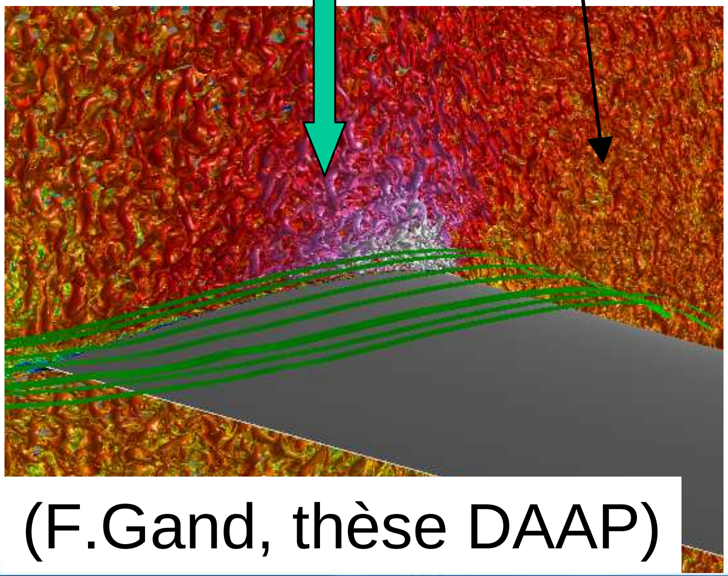
V. Brunet and S. Deck. 3rd Symposiun on hybrid RANS/LES, Gdansk, 2009)

(V.Brunet, DAAP)

DISCUSSION. Simulation de la turbulence pariétale à grand Re
Application aux écoulements de coins.



- traînée parasite, tremblement
- approche RANS mise en défaut
- besoin d'une meilleure fiabilité des simulations des écoulements de coins (design jonction voilure/fuselage)



(F.Gand, thèse DAAP)

- LES d'une jonction aile fuselage simplifiée
- Re_θ=2100. Re_c=3.10^5 M=0.15.
- Nxyz=65.10^6. Δt=0.5μs
- 8 processeurs NEC-SX8. 20000h CPU→80ms
- bonne comparaison avec les données exp.

•méthode de turbulence synthétique (SEM) (Pamiès et al. Phys. of Fluids, 21, 2009, thèse DAAP)
- étendu actuellement à la ZDES pour réduire le coût CPU

Conclusion

- Développement des méthodes RANS/LES incontournable et pour longtemps !

- Coût important de validation

→ Nécessité de validation de niveau > 3

→ Promotion d'expériences « calculables » (validation, fiabilité des calculs)

- Retour sur 2045 …

→ Si l'efficacité energétique des ordinateurs (J/flop ou kW.h/Giga.flop) approche un minimum, le coût nécessaire pour résoudre la CL turbulente à grand Reynolds sera inaccessible!

→ 2009: coût énergétique annuel (électricité)~5% du coût d'achat

→ Sera t'il rentable de simuler électroniquement le décollement turbulent !

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