A GLIMPSE AT WALL TURBULENCE

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THE FRENCH AEROSPACE LAB

return on innovation

Université Paris-Saclay

Plan

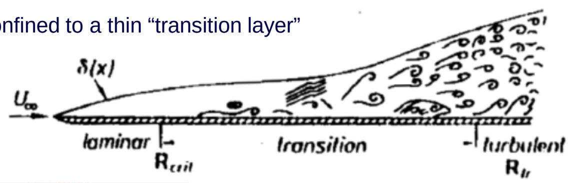
1. Basic knowledge of boundary layers
2. Statistical quantities
3. Wall-bounded flows simulations
4. A glimpse at high-Reynolds number wall-bounded flows
5. Applications

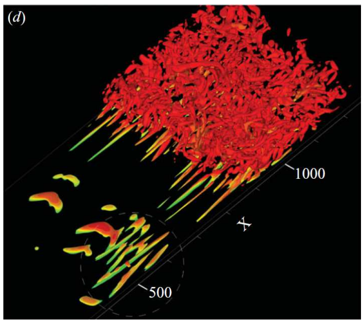
Laminar/turbulent boundary layer

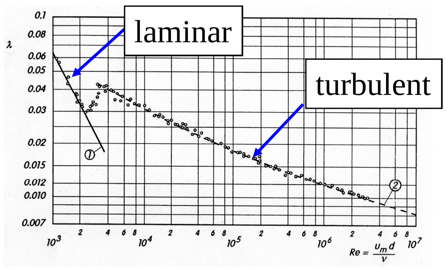
L. Prandtl, 1904, Heidelberg

- No slip at the wall
- Viscosity effect confined to a thin "transition layer"

(Schlichting, 8th edn)







Transition visualisation (Wu & Moin, JFM 2009)

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Remarks

- Turbulent flows are very different from their laminar counterpart:
  - Increased skin friction/pressure loss
  - Increased BL thickness
  - Increased heat/mass transfer properties
  - → technological importance!
- What are the associated physical mechanisms?
- Understanding is required to design/optimize systems and control devices

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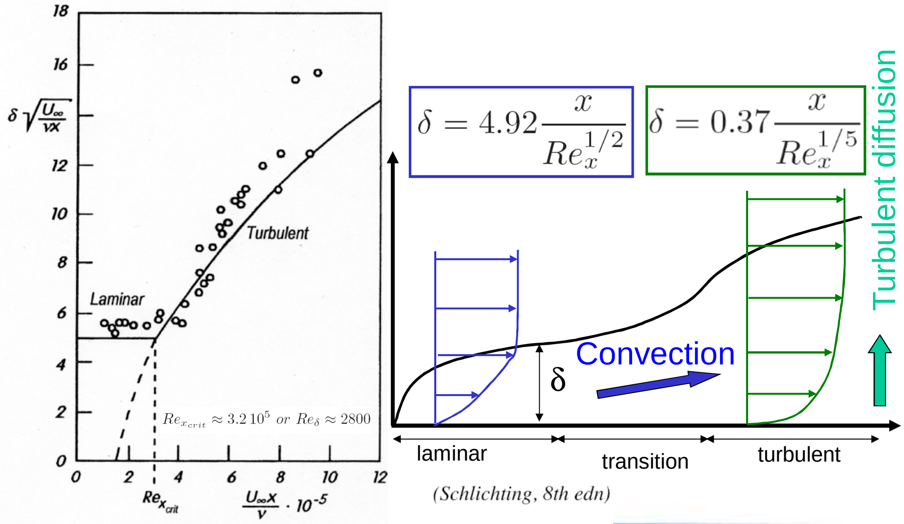
1. Introductory concepts: a glimpse at diffusion (cont'd)

- Growth of a flat plate boundary layer



(Schlichting, 8th edn)

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Global parameters (1/3)

Skin friction coefficient

$$C_f = \frac{\tau_p}{1/2\rho U_\infty^2} \qquad u_\tau = \sqrt{\tau_p/\rho} \qquad (\Rightarrow C_f/2 = u_\tau^2/U_\infty^2)$$

Boundary layer thickness based Reynolds number

$$Re_\delta = \delta U_\infty/\nu \quad Re_\tau = \frac{\delta u_\tau}{\nu} = \delta^+$$

Displacement and Rotta-Clauser thicknesses

$$\Delta = \frac{U_\infty}{u_\tau}\delta_1 = \int_0^\infty \frac{U_\infty - <u>}{u_\tau} dy$$

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Global parameters (2/3)

Momentum thickness

$$\theta = \int_0^\infty \frac{\langle u \rangle}{U_\infty}\left(1 - \frac{\langle u \rangle}{U_\infty}\right) dy \longrightarrow Re_\theta = \frac{\theta U_\infty}{\nu}$$

$$C_f/2 = d\theta/dx$$

Shape factor

$$H = \delta_1/\theta$$

Turbulent: H=1.3-1.4

Laminar: H=2.59

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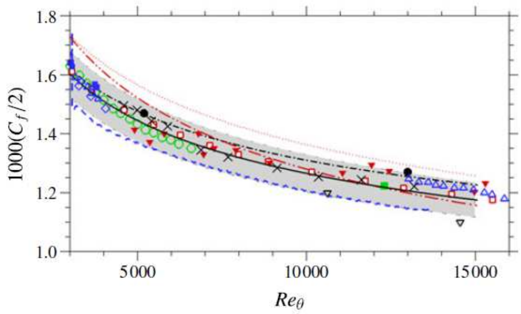
Global parameters (3/3)

	C_f	θ/x	δ_1/x	δ/x
Laminaire, Blasius	$0.664 \cdot Re_x^{-1/2}$	$0.664 \cdot Re_x^{-1/2}$	$1.721 \cdot Re_x^{-1/2}$	$4.92 \cdot Re_x^{-1/2}$
Turbulent, loi en 1/7 [49]	$0.0594 \cdot Re_x^{-1/5}$	$0.037 \cdot Re_x^{-1/5}$	$0.0477 \cdot Re_x^{-1/5}$	$0.38 \cdot Re_x^{-1/5}$
Turbulent, Michel [49]	$0.0368 \cdot Re_x^{-1/6}$	$0.0221 \cdot Re_x^{-1/6}$	$0.0309 \cdot Re_x^{-1/6}$	

	C_f	θ/x	δ_1/x	δ/x
Laminaire, Blasius	$0.441 \cdot Re_\theta^{-1}$	$0.441 \cdot Re_\theta^{-1}$	$1.143 \cdot Re_\theta^{-1}$	$3.268 \cdot Re_\theta^{-1}$
Turbulent, loi en 1/7 [49]	$0.026 \cdot Re_\theta^{-1/4}$	$0.0163 \cdot Re_\theta^{-1/4}$	$0.0209 \cdot Re_\theta^{-1/4}$	$0.167 \cdot Re_\theta^{-1/4}$
Turbulent, Michel [49]	$0.0172 \cdot Re_\theta^{-1/5}$	$0.0103 \cdot Re_\theta^{-1/5}$	$0.0144 \cdot Re_\theta^{-1/5}$	



Ref	Exp./DNS/Correlation	Symbol
DeGraaff & Eaton (2000)	*Exp.*	●
Österlund *et al.* (2000)	*Exp.*	□
Fernholz & Finley (1996)	*Exp.*	▼
Head & Bandyopadhyay (1981)	*Exp.*	▽
Nagib *et al.* (2007)	*Exp.*	■
Smith (1994)	*Exp.*	×
Erm & Joubert (1991)	*Exp.*	■
Schlatter & Örlü (2010*a*)	DNS	◇
Pirozzoli & Bernardini (2013)	DNS	△
Sillero *et al.* (2011)	DNS	○
Coles-Fernholz, best fit from Nagib *et al.* (2007)	$C_f = 2\left(\frac{1}{0.384}\ln(Re_\theta) + 4.127\right)^{-2}$	——
Schlichting (1968)	$C_f = 0.0256 Re_\theta^{-\frac{1}{4}}$	– · –
Michel *et al.* (1969)	$C_f = 0.0172 Re_\theta^{-\frac{1}{5}}$	· · ·
Spalart & Allmaras (1992)	RANS	– · –
present	ZDES	– – –

TABLE 3. List of symbols utilised in figure 5 and 7

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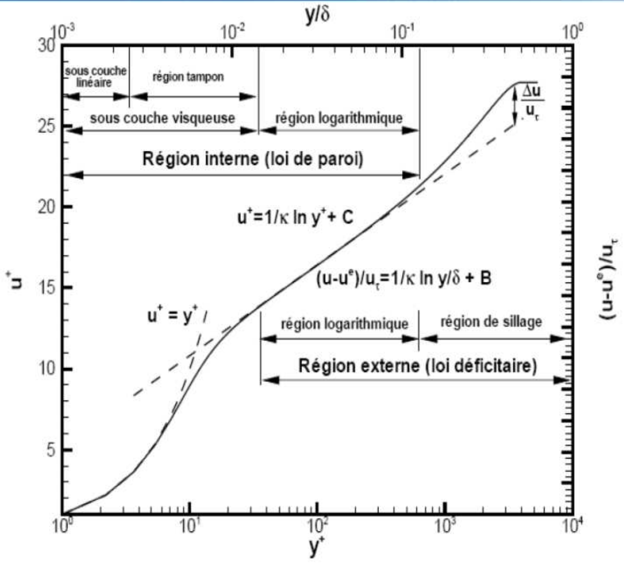
Mean Velocity



Reynolds stresses (1/3)

$$\partial_t \left\langle u'^2 \right\rangle + \langle u \rangle \partial_x \left\langle u'^2 \right\rangle + \langle v \rangle \partial_y \left\langle u'^2 \right\rangle = 2P (+A_u) + D_{iu} + C_u - D_{eu}$$

$$P = -\langle u'v' \rangle \partial_y \langle u \rangle$$
$$A_u = -2 \langle u'^2 \rangle \partial_x \langle u \rangle$$
$$D_{iu} = \partial_y (-\langle v'u'^2 \rangle + \nu \partial_y \langle u'^2 \rangle)$$
$$C_u = 2 \langle p' / \rho \, \partial_x u' \rangle$$
$$D_{eu} = 2\nu \langle \partial_{x_i} u' \partial_{x_i} u' \rangle$$

$$\partial_t \left\langle v'^2 \right\rangle + \langle u \rangle \partial_x \left\langle v'^2 \right\rangle + \langle v \rangle \partial_y \left\langle v'^2 \right\rangle = (A_v) + D_{iv} + C_v - D_{ev}$$

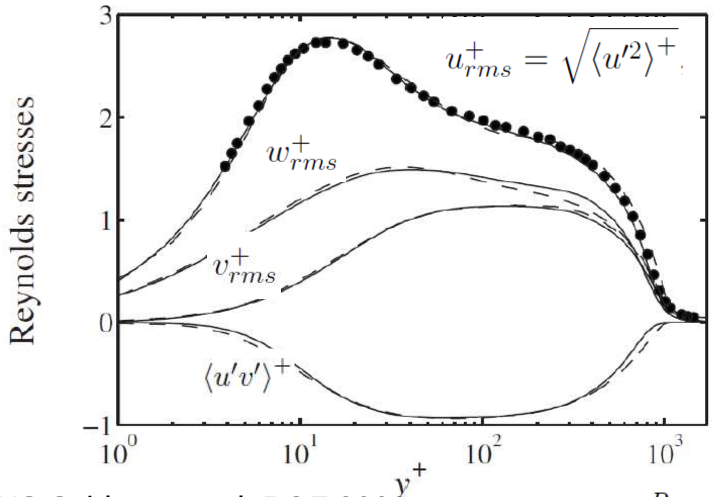
$$D_{iv} = \partial_y (-\langle v'^3 \rangle - 2 \langle p' / \rho \, v' \rangle + \nu \partial_y \langle v'^2 \rangle)$$
$$C_v = 2 \langle p' / \rho \, \partial_y v' \rangle$$
$$D_{ev} = 2\nu \langle \partial_{x_i} v' \partial_{x_i} v' \rangle$$

$$\partial_t \left\langle w'^2 \right\rangle + \langle u \rangle \partial_x \left\langle w'^2 \right\rangle + \langle v \rangle \partial_y \left\langle w'^2 \right\rangle = D_{iw} + C_w - D_{ew}$$

$$D_{iw} = \partial_y (-\langle v'w'^2 \rangle + \nu \partial_y \langle w'^2 \rangle)$$
$$C_w = 2 \langle p' / \rho \, \partial_z w' \rangle$$
$$D_{ew} = 2\nu \langle \partial_{x_i} w' \partial_{x_i} w' \rangle$$

$$C_u + C_v + C_w = 0.$$

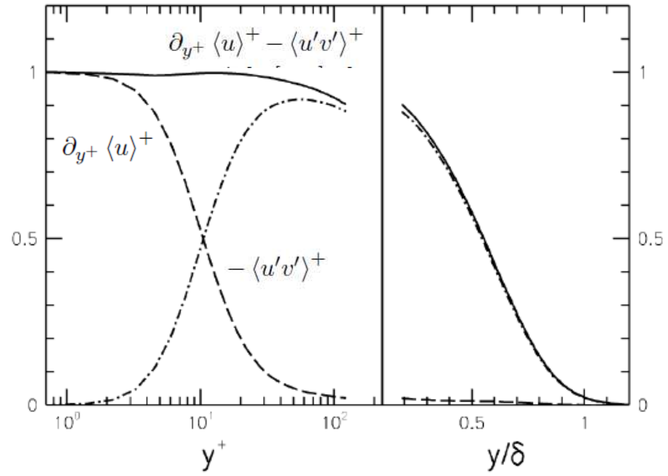
Reynolds stresses (2/3)



DNS Schlatter et al. POF 2009

$Re_\theta = 2\,541$

Reynolds stresses (3/3)



DNS Spalart, JFM 1988

$Re_\theta = 1410$

3. Statistical description in real space: Turbulent Kinetic Energy (TKE) equation.

Setting i=j in the Reynolds stress equation yields:

$$\frac{\bar{d}}{dt}\left(\rho \bar{k}\right) = -\rho\overline{u'_i u'_k}\frac{\partial \bar{U}_i}{\partial x_k} - \overline{\tau'_{ik}\frac{\partial u'_i}{\partial x_k}} - \frac{1}{2}\frac{\partial}{\partial x_k}\left[\rho\overline{u'_i u'_i u'_k}\right] - \overline{u'_i\frac{\partial p'}{\partial x_i}} + \frac{\partial}{\partial x_k}\left[\overline{u'_i \tau'_{ik}}\right]$$

ρ.P:Transfert term (production)

Rate of dissipation

Turbulent diffusion

Pressure diffusion

Viscous diffusion

→ Note that the term which transfers energy from the mean flow to turbulence appears in both mean and fluctuating KE equation but with an opposite sign

→ This latter term represents now the rate at which energy enters the turbulence and passes through the cascade

Rate of dissipation of TKE

$$\rho\epsilon \equiv \overline{\tau'_{ik}\frac{\partial u'_i}{\partial x_k}} = 2\mu\,\overline{s'^2_{ij}} = \frac{1}{2}\mu\overline{\left(\frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i}\right)^2} \geq 0 \qquad (\epsilon \sim \mathrm{m}^2.\mathrm{s}^{-3})$$

→ The rate at which energy is dissipated in regions where the instantaneous velocity gradients are large e.g. in the smallest eddies

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3. Statistical description in real space: Turbulent Kinetic Energy (TKE) equation (cont'd).

- Interpretation of $P \equiv -\rho\overline{u'_i u'_j}\frac{\partial \bar{U}_i}{\partial x_j}$. This term vanishes in the equation of the total (mean+fluctuating) kinetic energy.

→ exchange term of energy between the mean flow and turbulence

- $P = -\rho\overline{u'_i u'_j}\,\overline{S}_{ij}$

- In most turbulent flows, $P = -\rho\overline{u'_i u'_j}\frac{\partial \overline{U}_i}{\partial x_j} > 0$

→ production of turbulent energy by working of the mean flow on the turbulent Reynolds stresses.

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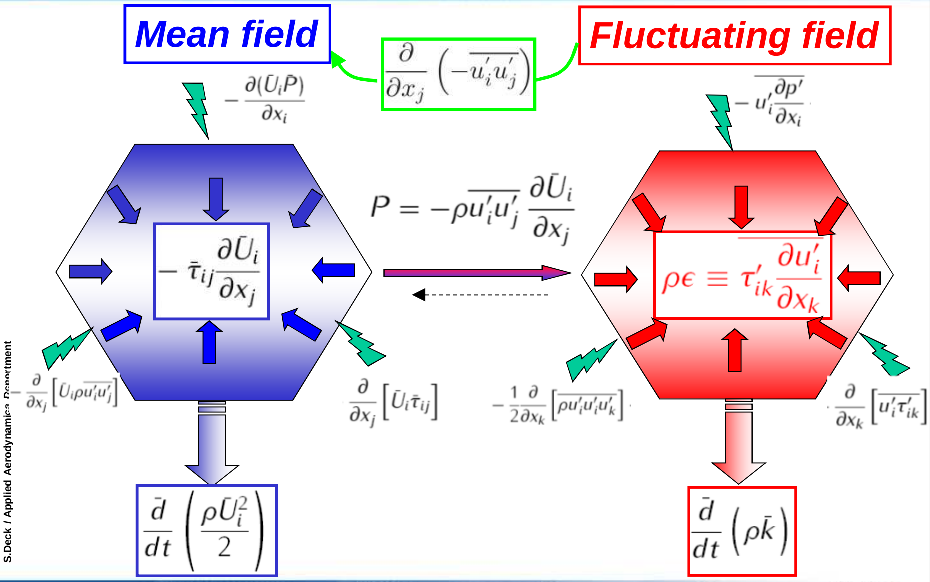
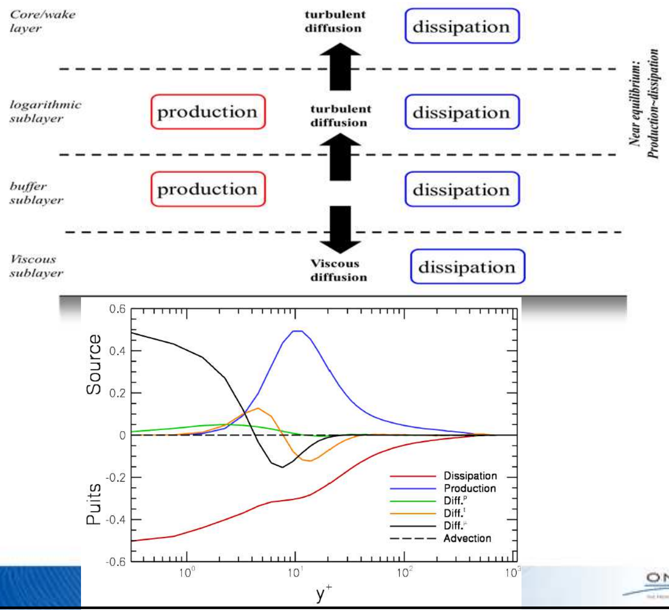
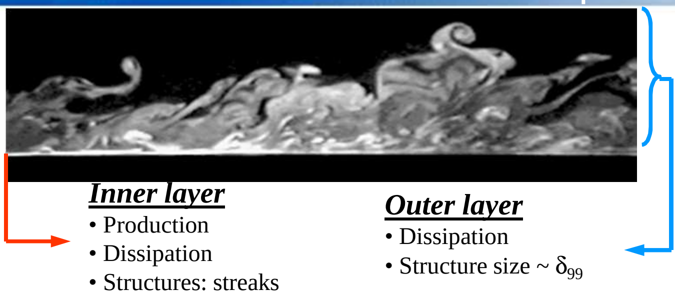
3. The exchange of energy between the mean flow and turbulence (cont'd).



Turbulent Kinetic Energy



Turbulent Boundary Layer Structure
Wall-bounded flows: the 2-scale problem



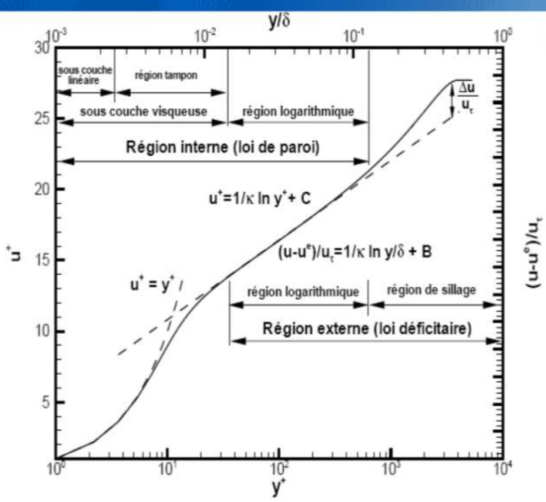
- Near a (smooth) wall, viscous mechanisms give rise to a viscosity based length scale (where *u'* is a characteristic turbulent velocity scale) $l_\nu \propto \nu / u'$

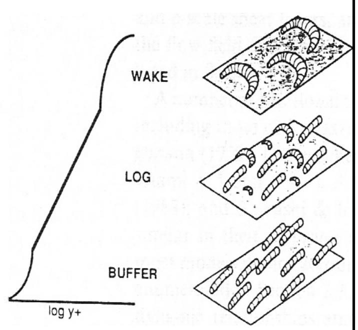
→The near wall dynamics (in the **wall/inner layer**) must be dominated by structures of this size

- The second « natural » (large) scale is the boundary layer thickness (or the pipe radius) δ_{99}. Structures of this size should govern the dynamics far from the wall (in the **outer layer**)

→ one expects from the existence of two regions an asymptotically matching in an intermediary **inertial layer**

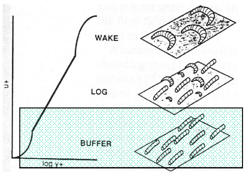
Turbulent Boundary Layer Structure

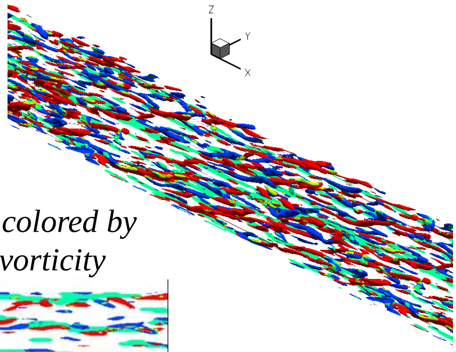




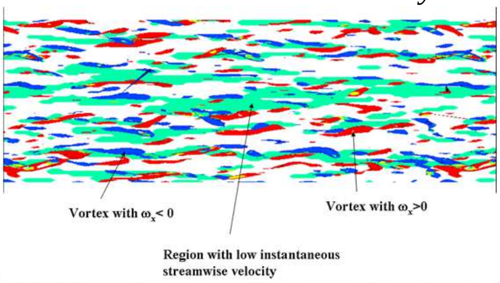
- The dynamics is associated with a very complex instantaneous flow organization
- Several types of flow structures are observed
- Each layer exhibits different coherent events
- Identification of the exact role of each structure is still an open controversial issue

Viscous and buffer layer





Q-criterion colored by streamwise vorticity



(adapted from E.Garnier)

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Viscous and buffer layer

- Low/high-speed Streamwise velocity streaks: sinuous arrays of alternating streamwise jets superimposed on the mean shear *(Kim & al., 1971)*
  - Average spanwise wavelength *z*+=50-100 *(Smith & al., 1983)*
  - Average streamwise length *x*+=1000
  - Wall shear is higher than the average at locations where the jets point forward (resp. backward) for high speed (resp. low speed) streaks
- Quasi-streamwise vortices
  - Slightly tilted from the wall (9 degrees)
  - Stay in the near-wall region only for *x*+=200 *(Jeong & al., 1997)*
  - Have a diameter ranging from 10 to 40+
  - Several vortices are associated with each streak, with longitudinal spacing *x*+=400
  - Some of them are connected to legs of hairpin vortices in the log layer, but most merge in incoherent vorticity away from the wall
  - Are advected at speed *c*+=10

(adapted from E.Garnier)

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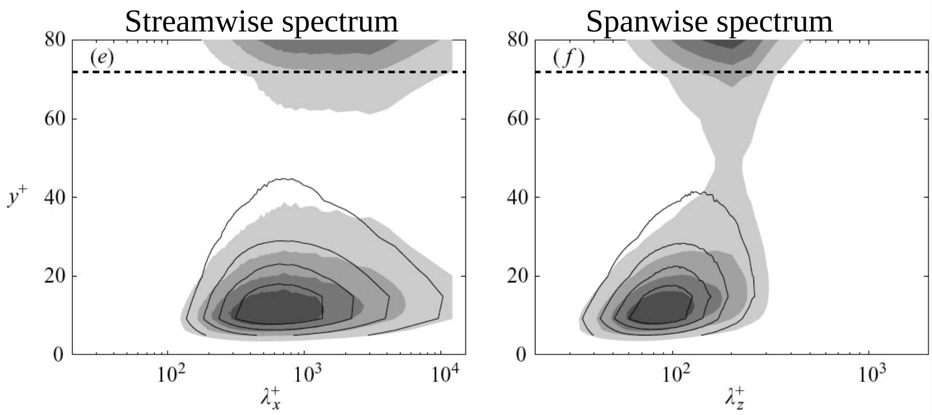
Viscous and buffer layer. Spectral analysis of TKE production

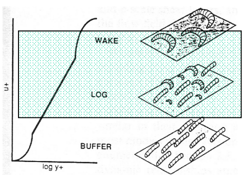


Conclusion: TKE production concentrated

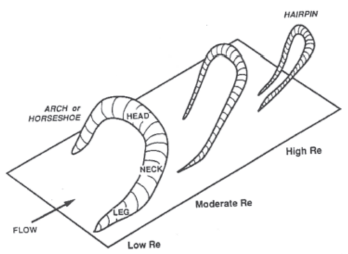
(Jimenez & al., 2004)

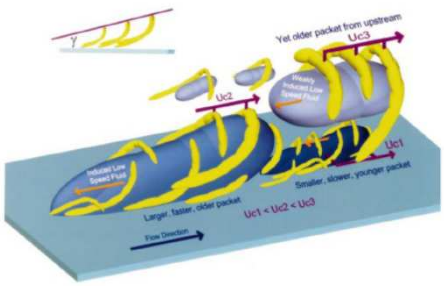
- below y^+=30,
- around $\lambda_x^+ \approx 600$ and $\lambda_z^+ \approx 100$

Log/wake region



Triggering of the outer cycle by the inner one





Re dependence of the hairpin shape. *Robinson 1991*

BL dynamics explained by hairpin packets. *Adrian JFM 2000*

Plan

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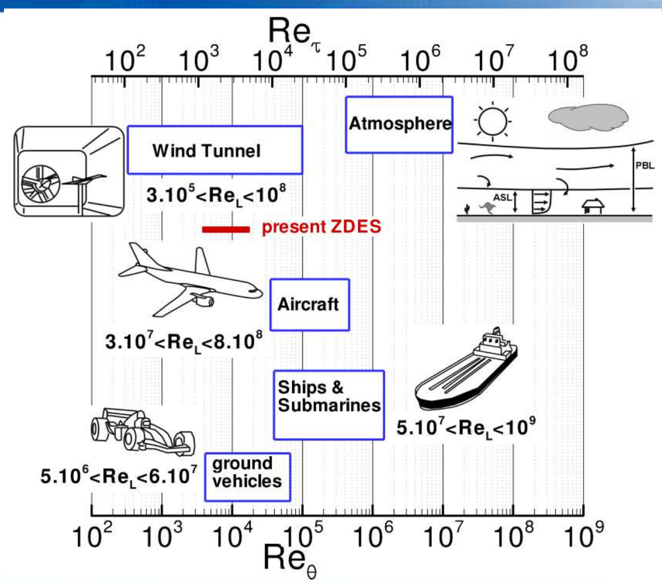
Computational cost



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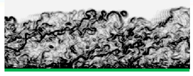
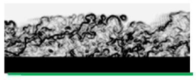
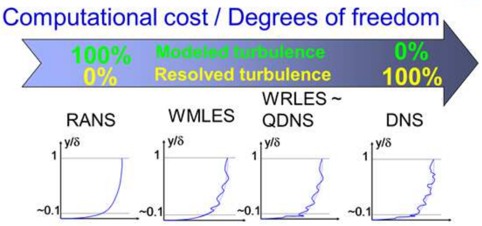
Computational cost

- Direct Numerical Simulation (**DNS**) : prohibitive



- Wall-Resolved Large Eddy Simulation (**WRLES**): Quasi-DNS (**inner zone**)
- Wall-Modelled LES (**WMLES**) : affordable at high Reynolds numbers (**modelled inner zone**)





Inner layer (y/δ ≤ 0.1)	*modeled*	*modeled*	*mostly resolved*	*fully resolved*
Outer layer	*modeled*	*mostly resolved*	*mostly resolved*	*fully resolved*

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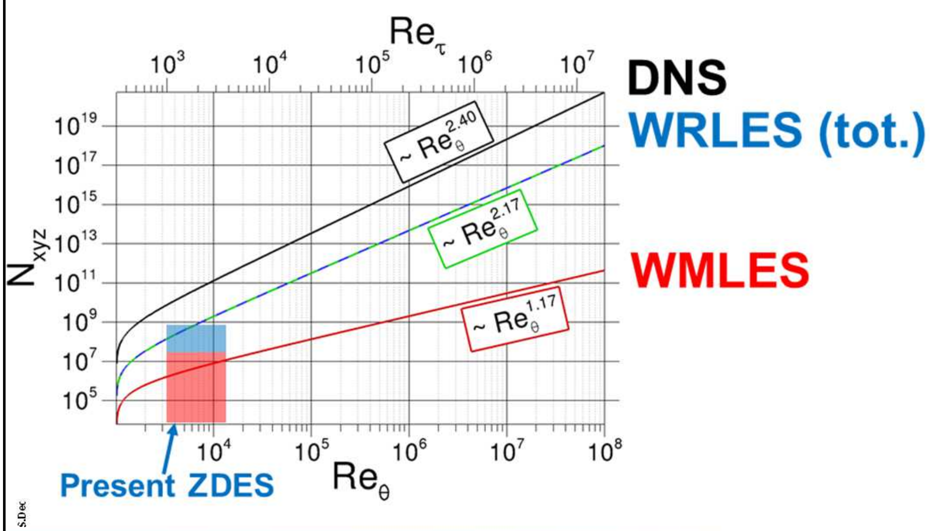

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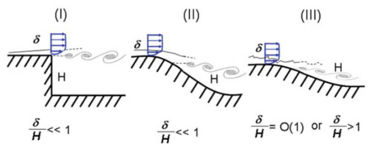
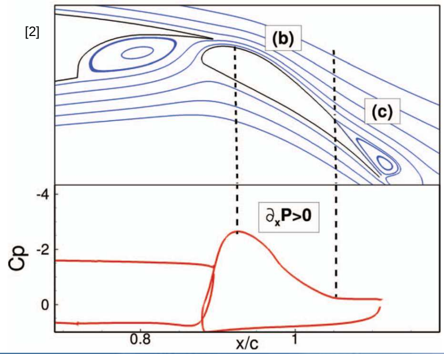
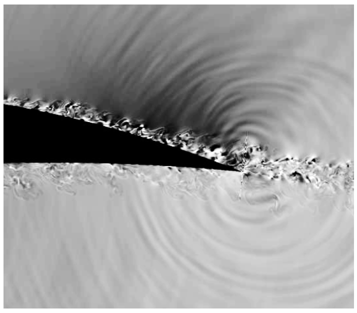
Wall-bounded turbulence-resolving simulations

- **Average** statistical description**: RANS (Reynolds-Averaged Navier-Stokes)**
- **Turbulence-resolving**:
  - Flow dominated by **history** of **upstream** boundary layer
  - Applications (**unsteady loads**, **aeroacoustics**…)



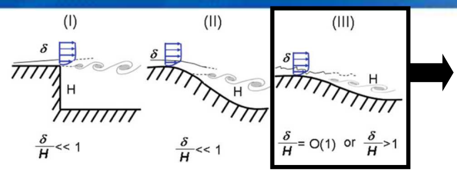
[1] Deck S., Recent improvements in the Zonal Detached Eddy Simulation (ZDES) formulation, *Theoretical Computational Fluid Dynamics*, 2012, 26, 523-550.





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

Zonal Detached Eddy Simulation (ZDES)



ZDES Mode III:
Wall-Modelled LES,
Wall-Resolved LES capability ([3])

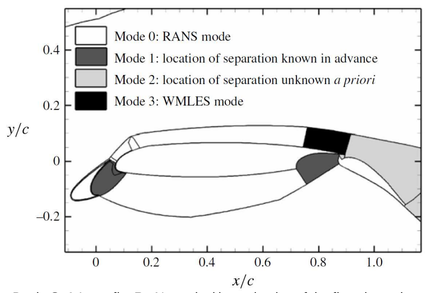
- **Multi-resolution** hybrid **RANS/LES** technique
- Ranging from RANS to **WRLES**, extensive **validation** basis

[1] Deck S., Recent improvements in the Zonal Detached Eddy Simulation (ZDES) formulation, *Theoretical Computational Fluid Dynamics*, 2012, 26, 523-550.

Deck S., Gand F., Brunet V. & Khelil S. B., High-fidelity simulations of unsteady civil aircraft aerodynamics: stakes and perspectives. Application of Zonal Detached Eddy Simulation (ZDES), *Philosophical Transactions of the Royal Society A*, 2014, 372:20130325.

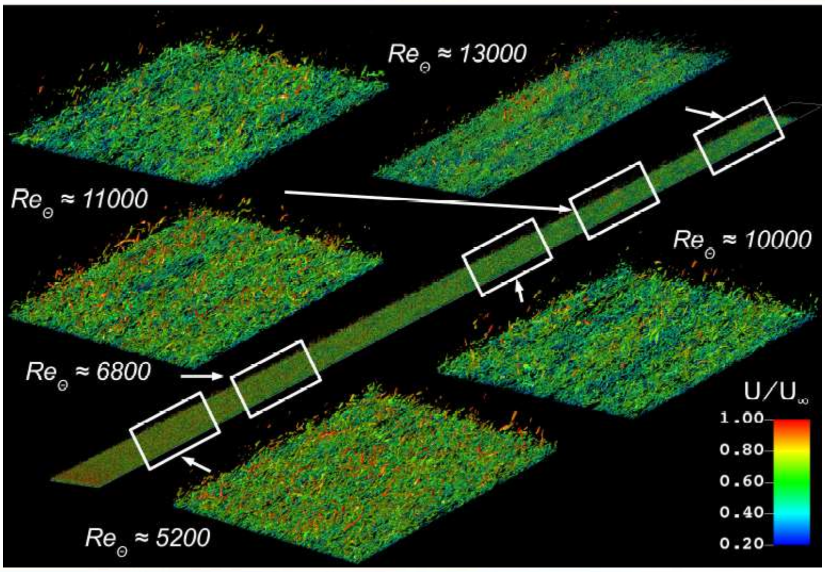
[3] Deck S., Renard N., Laraufie R. and Weiss P.-E., Large scale contribution to mean wall shear stress in high Reynolds number flat plate boundary layers up to Re_θ=13650, *Journal of Fluid Mechanics*, 2014, 743, 202-248

[4] Deck S., Renard N., Laraufie R. and Sagaut P., Zonal Detached Eddy Simulation of a spatially developing flat plate turbulent boundary layer over the Reynolds number range $3150 \le Re_\theta \le 14000$, *Physics of Fluids*, 2014, 26, 025116



Deck, S. & Laraufie, R., Numerical investigation of the flow dynamics past a three-element aerofoil, *Journal of Fluid Mechanics*, 2013, 732, 401-444

GENCI: projet ZDESWALLTURB



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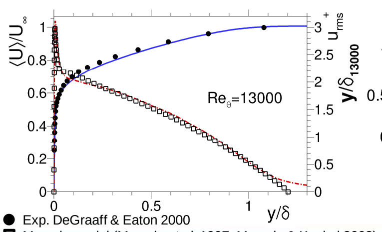
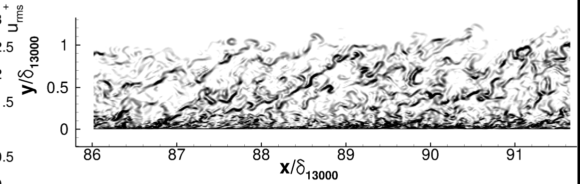
Wall-Resolved Large Eddy Simulation database

- WRLES of a **spatially developing** zero-pressure-gradient flat-plate turbulent **boundary layer**
- *$3060 \le Re_\theta \le 13650$, $L_x = 342\ \delta_0$, $M_\infty = 0.21$*
- **ZDES mode III**, *$\Delta x^+ = 50$, $\Delta z^+ = 12$, $N_{xyz} = 800.10^6$*
- **2.10^6 CPU hours** on **936** Nehalem processors of the CINES superscalar computer Jade-SGI Altix Ice 8200, **GENCI** project ZDESWALLTURB, **3 Terabytes** of data
- Low-dissipative AUSM+(P), FV, 2^{nd} order implicit time integration





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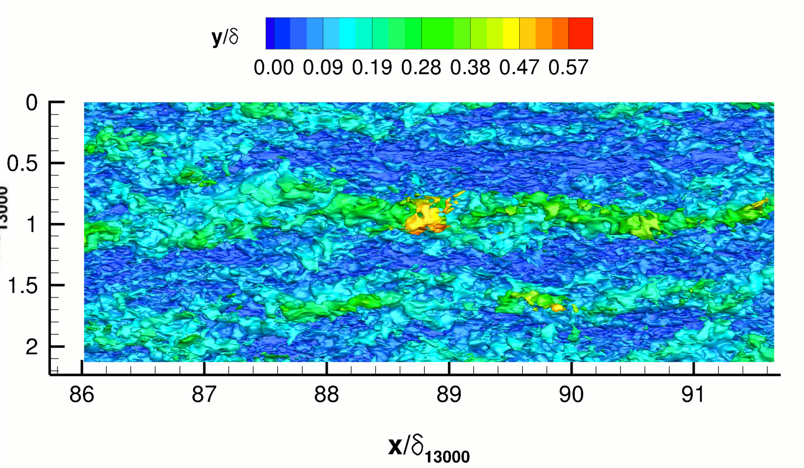
Flow visualization

- $Re_\theta \approx 13000$, $u^+=20$



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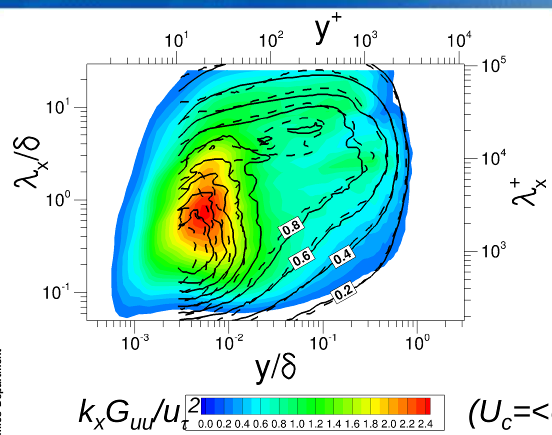
Streamwise PSD of *u'* at Re_θ=13000



(U_c=<U>(y))

- Power Spectral Density **estimation**: **Welch**'s method
- Time signal duration: $1155\ \delta_0/U_\infty$
- **Taylor**'s hypothesis $2\pi f = -k_x U_c$

Re_τ=3600, Re_θ=13000, present ZDES
Re_τ=2800, Exp. Mathis et al. 2009
Re_τ=3900, Exp. Marusic et al. 2010

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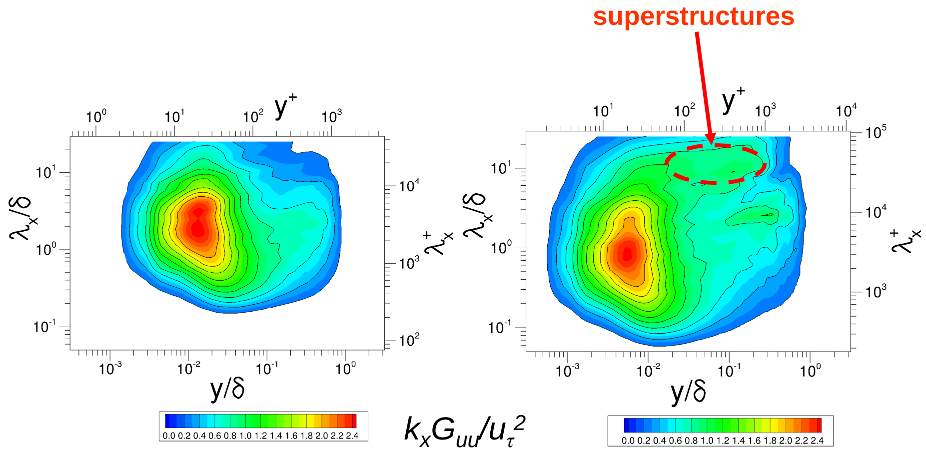
Streamwise PSD of *u'*: Reynolds number effect



$k_x G_{uu}/u_\tau^2$

$Re_\theta = 5200$ $(U_c=U_{corr}(y))$ $Re_\theta = 13000$

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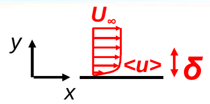
Analysis of mean skin friction: FIK identity



- **Contribution** of the **superstructures** to C_f?

  mean skin friction coefficient $C_f = \dfrac{\tau_w}{\frac{1}{2}\rho U_\infty^2}$ $\tau_w = \mu \dfrac{\partial \langle u \rangle}{\partial y}(y=0)$

- **FIK identity**: [6] Fukagata, K., Iwamoto, K. & Kasagi, N., Contribution of Reynolds stress distribution to the skin friction in wall-bounded flows, *Physics of Fluids*, 2002, 14, L73
  - Mean streamwise momentum equation, zero pressure gradient:

$$\frac{\partial \langle u \rangle}{\partial t} + \overline{I_x} = \frac{\partial}{\partial y}\left(\nu \frac{\partial \langle u \rangle}{\partial y} - \langle u'v' \rangle\right) \qquad \overline{I_x} = \frac{\partial}{\partial x}\left(\langle u \rangle^2\right) + \frac{\partial}{\partial y}\left(\langle u \rangle \langle v \rangle\right) - \nu \frac{\partial^2 \langle u \rangle}{\partial x^2} + \frac{\partial}{\partial x}\left(\langle u'^2 \rangle\right)$$

  - 3 integrations by parts over *y* later…

$$C_f = C_{f,1} + C_{f,2} + C_{f,3} \qquad C_{f,2} = -4\int_0^1 \frac{\langle u'v' \rangle}{U_\infty^2}\left(1 - \frac{y}{\delta}\right) d\left(\frac{y}{\delta}\right)$$

  - Reynolds shear stress distribution:

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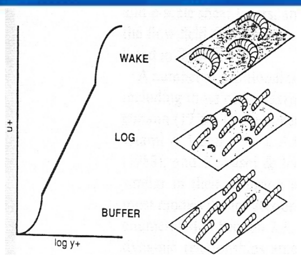
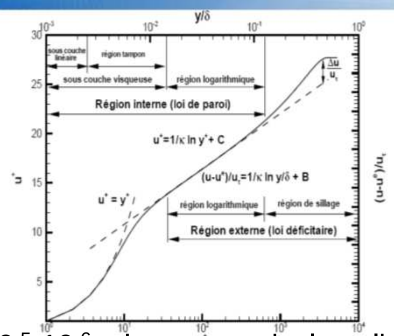
Grid requirements





RANS grid requirements:

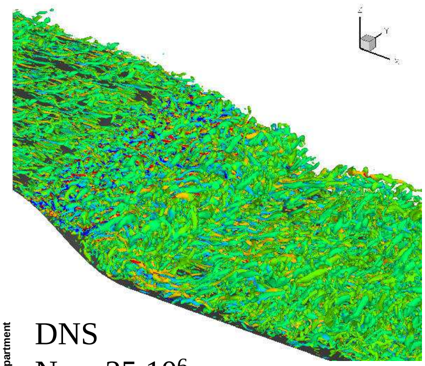
- $y^+<1$: f(Re), typically $\Delta y \sim\sim 10^{-5}$-$10^{-6}$m in aeronautical applications
- at least $N_y \sim 30$ points in δ , $d\delta/dx \sim$ 1cm/m
- $y_{i+1}/y_i < 1.1 \rightarrow N_y$

	Δx^+	Δy^+	Δz^+
LES	50	1	12
DNS	6	0.5	6

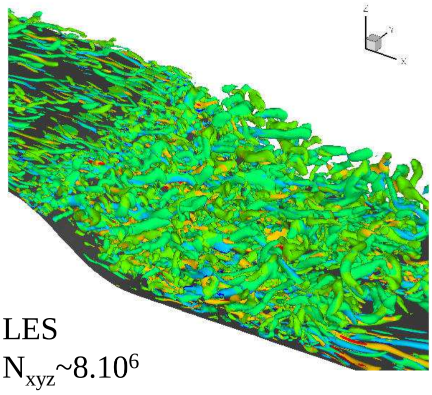
Plan

1. Basic knowledge of boundary layers
2. Statistical quantities
3. Wall-bounded flows simulations
4. A glimpse at high-Reynolds number wall-bounded flows
5. Applications

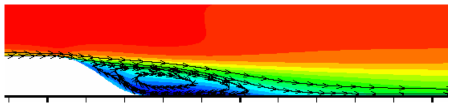
Separated flow over a S-shaped duct



DNS
$N_{xyz} \sim 25.10^6$



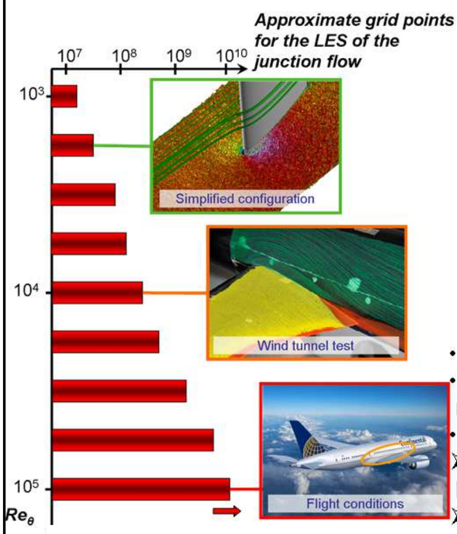
LES
$N_{xyz} \sim 8.10^6$



RANS
$N_{xyz} \sim 2.10^4$

(Courtesy of J.Dandois, ONERA)

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



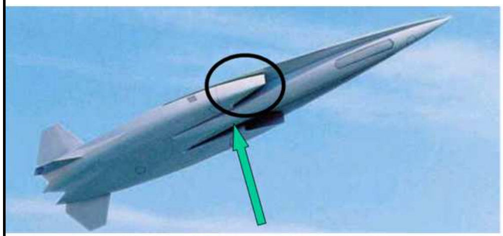
(F.Gand, PhD, ONERA)

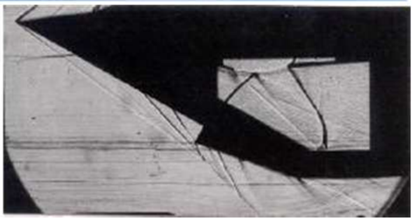
Description of the present LES:

- 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

Interaction Onde de Choc-Couche Limite Turbulente





Interaction Onde de Choc-Couche Limite Turbulente

(Courtesy of Jean-Paul Dussauge, IUSTI, Marseille)

Interaction Onde de Choc-Couche Limite Turbulente

Vaste Gamme d'échelles:

1. Épaisseur du choc: λ_{choc}
2. Échelle de Kolmogorov: η_K
3. Taille de la maille de calcul: Δx

- Simulation directe: $\Delta x \leq \lambda_{choc} \leq \eta_K$
- Simulation quasi-directe : $\lambda_{choc} \leq \Delta x \leq \eta_K$
- LES ou URANS: $\lambda_{choc} \leq \eta_K \leq \Delta x$

Coût d'une DNS

$$\text{computing time} \propto N_{xyz}.N_t \propto \tilde{C}.Re_L^3$$ (explicit schemes low CFL,…)

$\tilde{C}$ is the cost of the algorithm expressed in $[s/grid\ point/\ iteration]$

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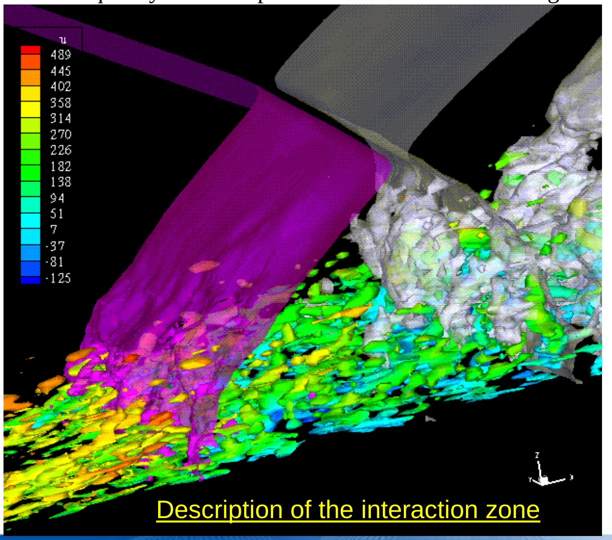
Oblique-Shock/boundary layer interaction (Ma=2.3)

- supersonic intake (unsteady distorsion)
- low-frequency shock displacement unsteadiness => large integration time



(LES, Courtesy of E. Garnier)

1. Grid requirements?
2. CPU cost ?

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