High-Fidelity Simulations for Turbulent Flows

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Part IV

Hybrid RANS/LES Methods

1 Introduction

2 Statistical approaches

3 Global approaches

4 Zonal approaches

5 Conclusion

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Historical background

SRANS

- May be forced, by grid or time step, on small components: brake lines, antennas, ..
- ✘ The least accurate (quite model-dependent)

2D URANS

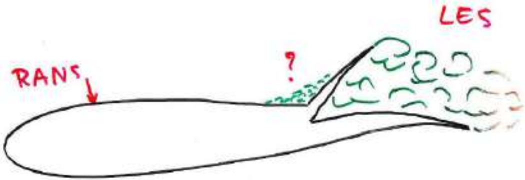
- ✔ Fits concept of resolved "coherent shedding" and modeled "random eddies"
- ✘ Lacks shedding modulations
- ✘ Over-predicts lift amplitude and drag

3D URANS

- ✔ Closer to reality than 2D URANS
- ✘ Quite delicate, model- and domain-size- dependent

Hybrids RANS-LES

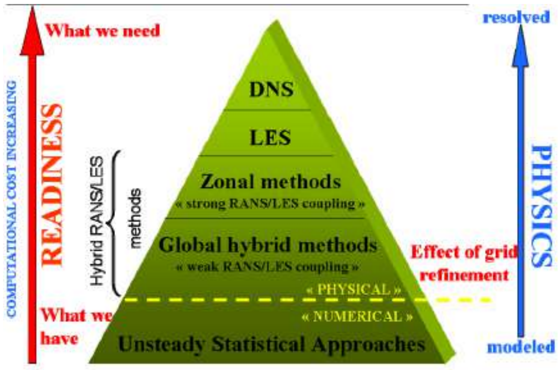
- ✔ Have the most physics
- ✔ Responds to grid refinement
- ✘ Most expensive
- ✘ Heaviest burden on user: grid, time step, domain
- ✘ Needs help from RANS in the BLs

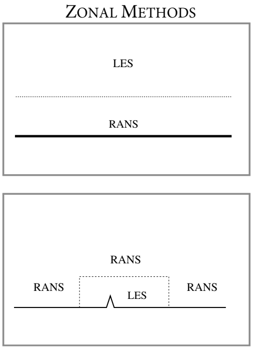


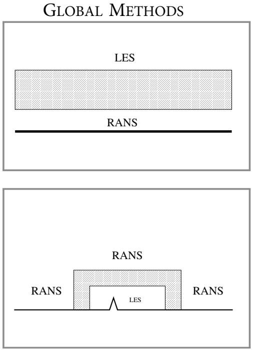
Sketch of DES in 1997 by Spalart (1997)

- Schumann (1975) Use of a model near the wall to circumvent the sgs model
- Germano et al. (1991) RANS and LES formally identical, only the scale-separation operator (i.e. the nature of the filter) changes
- Spalart (1997) Detached Eddy Simulation (DES): the whole boundary layer is treated in RANS
- Speziale (1998) Very Large Eddy Simulation (VLES): continuous RANS-DNS "universal" model
- Next: URANS, PANS, TRRANS, SAS, SDM, OES, VLES, LNS, XLES, DES, ZDES, DDES, SDES, "blending methods", "RANS/LES coupling", "embedded LES", ...

Hierarchy of Hybrid methods







Classification based on the nature of interface treatment

Zonal approach: domain divided into regions in which a pure LES or RANS model is applied

- Model discontinuity at the interface
- Definition of **jump** relations and **enrichment** / **restriction** operators

Global approach: a single set of equations blending RANS and LES models is applied everywhere

- Smooth RANS/LES transition
- Turbulent structures generated progressively through a **grey area**

Classifications

Unsteady Statistical Modelling Approaches

- URANS: Unsteady RANS
- SDM: Semi-Deterministic Method (Ha Minh, 1994)
- SAS: Scale Adaptive Simulation (Menter et al., 2003)
- TRRANS: Turbulence-Resolving RANS (Travin et al., 2004)

Zonal Hybrid Approaches

- Inlet Data Generation
  - Precursor calculation
  - Recycling methods (Lund et al., 1998)
  - Forcing methods
  - Synthetic Turbulence
    - Spectral methods
    - DF: Digital Filtering (Klein et al., 2003)
    - RFM: Random Fourier Modes (Kraichnan, 1970)
    - SEM: Synthetic Eddy Meth. (Pamiès et al., 2009)
- Setting of RANS/LES coupling
  - Full-variables approach
  - Non-Linear Disturbance Eqs (Morris et al., 1997)

Global Hybrid Approaches

- VLES: Very-LES (Speziale, 1998)
- LNS: Limited Numerical Scales (Batten et al., 2002)
- PG: Perot & Gadebush model (Perot and Gadebusch, 2007)
- Blending or "hybrid viscosity" methods (Baggett, 1998; Menter, 1994; Fan et al., 2002; Baurle et al., 2003)
- PITM: Partially-Integrated Transport Model (Chaouat and Schiestel, 2005)
- PANS: Partially-Averaged NS (Girimaji, 2006)
- DES: Detached Eddy Simulation
  - SA-DES (Spalart, 1997)
  - k_t-ε-DES (Strelets, 2001)
  - XLES: Extra-LES (Kok et al., 2004)
- DDES: Delayed DES (Spalart et al., 2006)
- ZDES: Zonal DES (Deck, 2005b)

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Unsteady Statistical approaches

Scale Adaptive Simulation (SAS)

(Menter et al., 2003)

Based on k_t-ε, assuming $\mathcal{P} = \varepsilon$ and $\sigma_k = \sigma_\varepsilon$:

$$\frac{\mathrm{d}\mu_t}{\mathrm{d}t} = \underbrace{c_1 \mu_t S}_{\text{prod.}} - \underbrace{c_2 \rho \left(\frac{\nu_t}{L_{\text{vK-SAS}}} \right)^2}_{\text{destr.}} + \underbrace{\nabla \cdot \left(\frac{\mu_t}{\sigma} \nabla \nu_t \right)}_{\text{diff.}}$$

$$\text{with } L_{\text{vK-SAS}} = \kappa \left| \frac{u'}{u''} \right| = \kappa \left| \frac{\frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j}}{\frac{\partial^2 u_i}{\partial x_m^2} \frac{\partial^2 u_i}{\partial x_n^2}} \right|$$

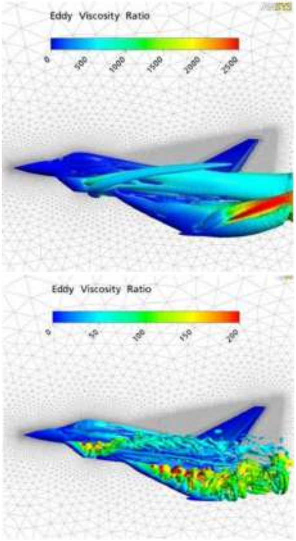
- In shear regions, where instabilities generate coherent structures, model turns to LES
- Independent from d_w
- Later, $L_{\text{vK-SAS}} = \max \left[\kappa \left| \frac{u'}{u''} \right|, \underbrace{C_{\text{SAS}}}_{=0.6} \Delta \right]$

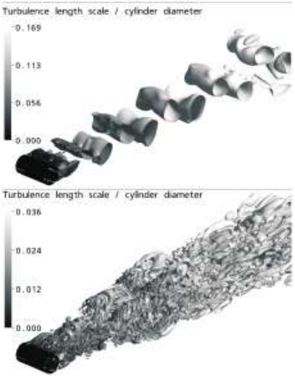
✔ Detect resolved unsteady struct. and reduce ν_t

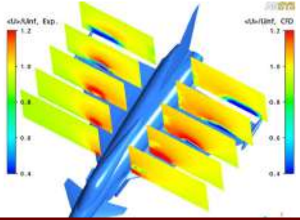
✘ ... but ν_t often too high

✘ Model ill-posed ($u'' = 0$ at inflexion points)

Top: SST-URANS; bottom: SST-SAS







Statistical approaches

Turbulence-Resolving RANS (TRRANS)
(Travin et al., 2004)

- Based on the k_t-ω model:

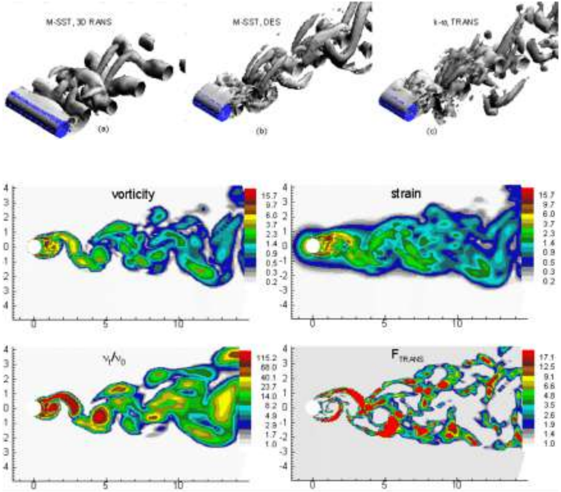
$$D_k^{\text{TRRANS}} = \overbrace{(C_\mu \omega k_t)}^{D_k^{\text{RANS}} \equiv \varepsilon_{\text{RANS}}} \cdot F_{\text{TRRANS}}$$

$$F_{\text{TRRANS}} = \max\left[\left(\frac{S}{C_{\text{TRRANS}}\Omega}\right)^2, 1\right]$$

with $C_{\text{TRRANS}} = 1.25$ (calibrated by DHIT)

- $S \approx \Omega$ (shear layers) or $S \ll \Omega$ (vortices):
  TRRANS = RANS
- $S \gg \Omega$ (strain-dominated flows):
  larger $\varepsilon \rightarrow$ smaller ν_t ($\nu_t = C_\mu k_t^2/\varepsilon$)

✔ Response to grid refinement as LES (smaller structures resolved as $\Delta \downarrow$)



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Global hybrid approaches: VLES and LNS

Very Large Eddy Simulation (VLES)

(Speziale, 1998)

Idea: damp the modeled stresses when $\Delta \sim \eta$

$$\tau_{ij} = \alpha \tau_{ij}^{\mathrm{RANS}}$$

with

$$\alpha = \left[1 - \exp\left(-\frac{\beta\Delta}{\eta}\right)\right]^n \quad \text{and} \quad \eta = \left(\frac{\nu^3}{\bar{\epsilon}}\right)^{\frac{1}{4}}$$

- ✔ $\Delta/\eta \to 0$: DNS behavior, *i.e.* $\tau \simeq 0$
- ✔ $\Delta/\eta \to \infty$: RANS behavior, *i.e.* $\tau \simeq \tau^{\mathrm{RANS}}$
- ✔ $0 \leq \alpha \leq 1$: VLES mode
- ✔ $Re \to \infty$, $\eta \to 0$, $\alpha = 1$, $\forall\Delta$ (*i.e.* no more influence of the grid)
- ✔ any RANS model can be blended
- ✘ β and n not specified ...
- ✘ Recovering RANS and DNS does not ensure correct LES behavior

Limited Numerical Scales (LNS)

(Batten et al., 2002)

Idea: α defined by the ratio of the effective viscosities

$$\alpha = \frac{\min\left[(\ell u)_{\mathrm{LES}}, (\ell u)_{\mathrm{RANS}}\right]}{(\ell u)_{\mathrm{RANS}}}$$

- ✔ no new constants
- ✔ allow hybridization of every RANS/LES models

Example: k_t-ε + Smagorinsky linear model

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

$$\alpha = \min\left[\frac{\nu_t^{\mathrm{LES}}}{\nu_t^{\mathrm{RANS}} + 10^{-20}}, 1\right] = \min\left[\frac{C_{\mathrm{smag}}\Delta^2 S}{C_\mu}\frac{\varepsilon}{k_t^2} + 10^{-20}, 1\right]$$

- ✔ Easy implementation
- ✘ As good as underlying RANS/LES models

Global hybrid approaches: Blending methods

Method I - Idea (Baggett, 1998): combination of turbulent/subgrid viscosities

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -\left[(1-\Gamma(d_w))\nu_t^{\mathrm{LES}} + \Gamma(d_w)\,\nu_t^{\mathrm{RANS}}\right]\overline{S}_{ij}$$

- $\Gamma(d_w)$: matching function, parameterized with $\dfrac{\Delta}{L_\varepsilon}$ where L_ε is the turbulent integral dissipation length

Method II - Idea (Fan et al., 2002): replace turbulence model by subgrid model outside the BL:

$$[\text{hybrid RANS/LES viscosity}] = \Gamma[\text{RANS eddy viscosity}] + (1-\Gamma)[\text{LES SGS viscosity}]$$
$$[\text{hybrid RANS/LES TKE equation}] = \Gamma[\text{RANS TKE equation}] + (1-\Gamma)[\text{LES TKE equation}]$$

- Objective: define Γ s.t. $\Gamma = 1$ in the BL and "quickly" $\rightarrow 0$ outside (LES)
- Can be applied to every turbulent/subgrid models
- Close to the idea of Menter (1994) for the RANS model k-ω:

$$[\text{Menter's hybrid model}] = F_1[k_t - \omega \text{ model}] + (1-F_1)[k_t - \varepsilon \text{ model}]$$

Application of blending method of Fan et al. (2002)

- k_t-ω model near the wall + one-equation subgrid model away from the wall

The kinetic energy equation is modified as:

$$(\mathrm{I})\quad \frac{\mathrm{d}k_t}{\mathrm{d}t} = \underbrace{\nu_t\Omega^2}_{\mathcal{P}_k} - \left[\Gamma\,\underbrace{(C_\mu k_t\omega)}_{\varepsilon_{\text{RANS}}} + (1-\Gamma)\,\underbrace{C_d\frac{k_t^{3/2}}{\Delta}}_{\varepsilon_{\text{LES}}}\right] + \text{diffusion} \qquad \text{with} \qquad (\mathrm{II})\quad \nu_t = \Gamma\,\underbrace{\frac{k_t}{\omega}}_{\nu_t^{\text{RANS}}} + (1-\Gamma)\,\underbrace{C_s\sqrt{k_t}\Delta}_{\nu_t^{\text{LES}}}$$

Γ is a modification of the one of Menter (1994):

$$\Gamma = \tanh(\eta^4) \qquad \text{with} \qquad \eta = \frac{1}{\omega}\max\left(\frac{\sqrt{k_t}}{C_\mu d_w}, \frac{500\nu}{d_w^2}\right)$$

Limit of balancing subgrid production and dissipation ($\Gamma = 0$):

- One obtains a Smagorinsky-type eddy viscosity:

$$\nu_t = C_s\sqrt{\frac{C_s}{C_d}}\Delta^2\Omega = C_F\Delta^2\Omega$$

with C_F ranging from 0.1 to 0.31 (wrt C_S=0.18)

- Combination of (I) and (II) gives a one-equation model for the transport of subgrid viscosity

$$\frac{\mathrm{d}\nu_t}{\mathrm{d}t} = \frac{C_s}{2}(C_s\Delta^2\Omega^2 - C_d k_t) + \text{diffusion}$$

k_t acts as a destruction term for ν_t!

✘ This method forces LES away from the walls even if the mesh is too coarse

✘ This results in lower Reynolds stresses compared to the RANS model (gray-area) $\Longrightarrow$ How can avoid it?

*Variations of the blending method

Modifications to the approach of Fan et al. (2002):

- Baurle et al. (2003) proposes a different blending function:

$$\Gamma = \max[\tanh(\eta^4), \widetilde{\alpha}_{\mathrm{LNS}}] \qquad \text{with} \qquad \widetilde{\alpha}_{\mathrm{LNS}} = \mathrm{int}\left[\min\left(\frac{\nu_t^{\mathrm{LES}}}{\nu_t^{\mathrm{RANS}}}, 1\right)\right]$$

  - $\widetilde{\alpha}_{\mathrm{LNS}}$ ensures the RANS behavior if $\nu_t^{\mathrm{LES}} > \nu_t^{\mathrm{RANS}}$

- Xiao et al. (2004) compared several blending functions:

$$\Gamma_{vK} = \tanh\left(\frac{L_{vK}}{\alpha_1\lambda}\right)^2, \qquad \Gamma_{d_w} = \tanh\left(\frac{d_w}{\alpha_1\lambda}\right)^2, \qquad \Gamma_{\Delta} = \tanh\left(\frac{L_{\mathrm{RANS}}}{\alpha_2\Delta}\right)^2$$

  - They indicate that Γ has to be a non-decreasing function as d_w increases
  - Γ_{Δ} close to DES

- Stress-Blended Eddy Simulation (SBES) of Menter (2016): $\tau_{ij} = \Gamma\tau_{ij}^{\mathrm{RANS}} + (1-\Gamma)\tau_{ij}^{\mathrm{LES}}$
  - If both models are eddy-viscosity models, it reduces to $\nu_t = \Gamma\nu_t^{\mathrm{RANS}} + (1-\Gamma)\nu_t^{\mathrm{LES}}$
  - Model used by ANSYS, blending function Γ kept secret

*PITM/PANS

- Previous methods rely on appropriate modifications of scale-determining equations
- PITM/PANS rely on reduction of destruction term in a model dissipation equation

Partially Integrated Transport Model (PITM)

(Chaouat and Schiestel, 2005)

- Write equation for ε_{sgs}
- RANS-type eq., with non-constant coeffs

$$\frac{\mathrm{d}\varepsilon_{\text{sgs}}}{\mathrm{d}t} = C_{\varepsilon 1}\frac{\varepsilon_{\text{sgs}}}{k_{\text{sgs}}}\mathcal{P}_{k_{\text{sgs}}} - \underbrace{\left[C_{\varepsilon 2} - \frac{k_{\text{sgs}}}{k_t}(C_{\varepsilon 2} - C_{\varepsilon 1})\right]}_{C^*_{\varepsilon 2}}\frac{\varepsilon^2_{\text{sgs}}}{k_{\text{sgs}}} + \mathcal{D}_{\varepsilon_{\text{sgs}}}$$

- $\dfrac{k_{\text{sgs}}}{k_t}$ can be calibrated as a function of κ_{cutoff}
- Asymptotic behavior:

$$\frac{k_{\text{sgs}}}{k_t} \approx \frac{3C_K}{2}\eta_c^{-2/3}$$

$$\nu_{\text{sgs}} = \frac{1}{\pi^2}\left(\frac{3C_K}{2}\right)^3 C_\mu^{3/2}\Delta^2|\overline{S}_{ij}|$$

✔ Sound spectral basis

✘ Only applied to academic configurations so far

Partially Averaged Navier–Stokes (PANS)

Girimaji (2006)

- Based on the unresolved-to-total ratios

$$f_k = \frac{k_u}{k_t} \qquad f_\varepsilon = \frac{\varepsilon_u}{\varepsilon}$$

- Modification of σ_k and σ_ε in $k_t - \varepsilon$ model

$$C^*_{\varepsilon 2} = C_{\varepsilon 1} + \frac{f_k}{f_\varepsilon}(C_{\varepsilon 2} - C_{\varepsilon 1})$$

$$\sigma^*_k = \frac{f_k^2}{f_\varepsilon}\sigma_k \qquad f_k = \frac{1}{\sqrt{C_\mu}}\left[\frac{\Delta}{k^{3/2}/\varepsilon}\right]^{2/3}$$

- $f_k = 1$: PANS = RANS
- $f_k = 0$: remove all modeling
- $0 < f_k < 1$: Partially-resolved turbulence

✘ Fixed ratios, more similar to Statistical than Hybrid RANS/LES methods

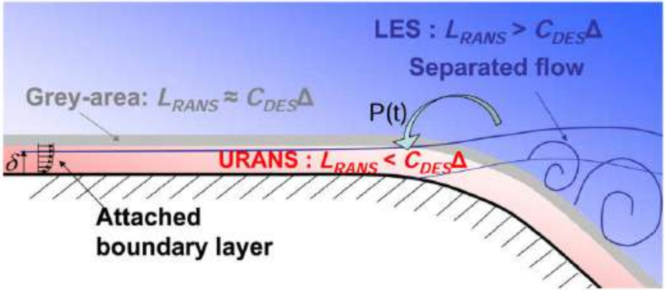
Detached Eddy Simulation (DES)

From Travin et al. (2000): "*A Detached Eddy Simulation is a 3D unsteady numerical solution using a single turbulence model, which functions as a SGS model in regions where the grid density is fine enough for a LES, and as a RANS model in regions where it is not.*"

Idea (Spalart, 1997): Start from a RANS formulation and modify the lengthscale in the RANS equations

$$\boxed{L_{\mathrm{DES}} = \min(L_{\mathrm{RANS}}, C_{\mathrm{DES}}\Delta)}$$

with $\Delta = \max(\Delta x, \Delta y, \Delta z)$ and C_{DES} a constant to be determined.



- $L_{\mathrm{RANS}} < C_{\mathrm{DES}}\Delta$: original RANS behavior
- $L_{\mathrm{RANS}} > C_{\mathrm{DES}}\Delta$: grid-dependent ν_t
- $L_{\mathrm{RANS}} \sim C_{\mathrm{DES}}\Delta$: **grey area**

Initial formulation:

- Based on SA model
- Named DES97 by Spalart et al. (2006)

DES applied to the Spalart–Allmaras model (1)

$$\frac{\partial \nu_{sa}}{\partial t} + \widetilde{u}_j \frac{\partial \nu_{sa}}{\partial x_j} = c_{b1} S_{sa} \nu_{sa} - c_{w1} f_w^{DES} \left(\frac{\nu_{sa}}{d}\right)^2 + \frac{1}{\sigma}\left[\frac{\partial}{\partial x_k}\left((\widetilde{\nu} + \nu_{sa})\frac{\partial \nu_{sa}}{\partial x_k}\right) + c_{b2}\frac{\partial \nu_{sa}}{\partial x_k}\frac{\partial \nu_{sa}}{\partial x_k}\right]$$

$$\mu_t = \rho \nu_{sa} f_{v1} \qquad S_{sa} = \sqrt{2\widetilde{\Omega}_{ij}\widetilde{\Omega}_{ij}} + \frac{\nu_{sa}}{\kappa^2 d^2} f_{v2} \qquad \widetilde{\Omega}_{ij} = \frac{1}{2}\left(\frac{\partial \widetilde{u}_i}{\partial x_j} - \frac{\partial \widetilde{u}_j}{\partial x_i}\right) \qquad f_{v1} = \frac{\chi^3}{\chi^3 + c_{v1}^3} \qquad f_{v2} = 1 - \frac{\chi}{1 + \chi f_{v1}}$$

$$\chi = \frac{\nu_{sa}}{\widetilde{\nu}} \qquad f_w^{DES} = g\left(\frac{1 + c_{w3}^6}{g^6 + c_{w3}^6}\right)^{1/6} \qquad g = r + c_{w2}(r^6 - r) \qquad r^{DES} = \frac{\nu_{sa}}{S_{sa}\kappa^2 d^2}$$

- Spalart (1997) proposes to replace d_w with $\boxed{\tilde{d} = \min(d_w, C_{DES}\Delta)}$ ($C_{DES} = 0.65$ from DHIT)

What is its **asymptotic behavior?**: **equilibrium hypothesis + high-Re limit**

1) High-Re limit: $\nu_{sa} = \nu_t, \quad \widetilde{d} = C_{DES}\Delta$

2) Equilibrium: $P = \varepsilon$ thus

$$c_{b1} S_{sa} \nu_{sa} = c_{w1} f_w^{DES}\left(\frac{\nu_{sa}}{C_{DES}\Delta}\right)^2$$

$$\Longrightarrow \quad \nu_t = \nu_{sa} = \frac{c_{b1}}{c_{w1} f_w^{DES}} C_{DES}^2 \Delta^2 S_{sa}$$

In the asymptotic limit, DES97 is approx. equivalent to a **Smagorinsky model** with $C_s = 0.2$

- How to compute f_w^{DES}? Noticing that

$$r^{DES} = \frac{\nu_t}{S_{sa}\kappa^2 C_{DES}^2 \Delta^2} = \frac{c_{b1}}{f_w^{DES} c_{w1}\kappa^2}$$

$$\Longrightarrow \quad f_w^{DES} = g(f_w^{DES})\left(\frac{1 + c_{w3}^6}{g(f_w^{DES})^6 + c_{w3}^6}\right)^{1/6} = 0.424$$

(the only acceptable physical root) Hence,

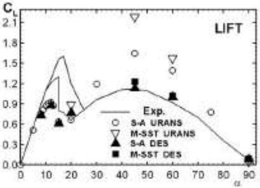
$$\nu_t = \frac{c_{b1}}{c_{w1} f_w^{DES}} C_{DES}^2 \Delta^2 S = \underbrace{\widetilde{C}_s^2}_{=0.2^2} \Delta^2 S$$

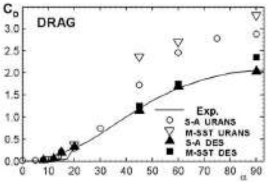
DES: Comparison URANS/DES

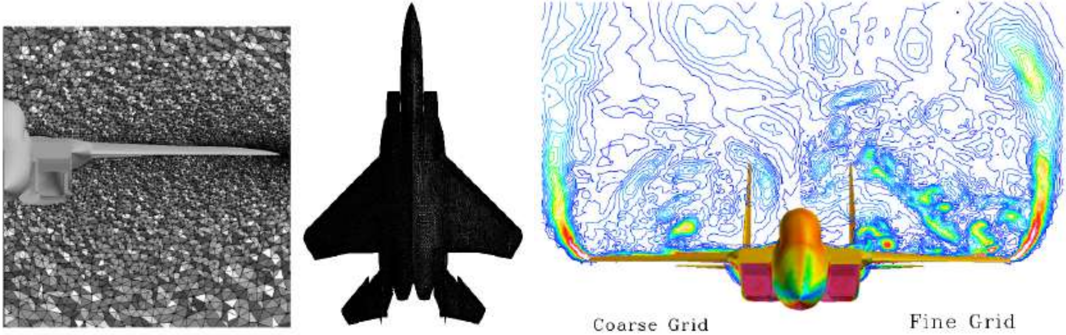
- Strelets (2001) introduce DES based on k_t-ω SST

Lift and drag coefficient for NACA0012: comparison URANS/DES/experimental data

- Beyond stall (especially for $\alpha \geq 30°$), URANS suffers from a very large drag and lift, whereas DES-SST and DES-SA are in fair agreement with exp.







DES of a F-15E fighter. Re_c=$13.6 \cdot 10^6$, M=0.3. Fine grid $10 \cdot 10^6$ cells, coarse grid: $2.85 \cdot 10^6$ cells. From Forsythe et al. (2004).

*Extra-Large Eddy Simulation (XLES)

Problems with DES-SA and DES-SST:

- They return a SM-like model only with asymptotic behavior
- SGS model no clearly defined

Idea (Kok et al., 2004): Explicit definition of the subgrid model and of the dissipation rate

$$L_{\mathrm{XLES}} = \min(L_{\mathrm{RANS}}, C_1\Delta) \qquad \text{with} \quad \nu_t = L_{\mathrm{XLES}}\sqrt{k_t} \quad \text{and} \quad \varepsilon = C_\mu \frac{k_t^{3/2}}{L_{\mathrm{XLES}}}$$

Hence:

- Mode RANS: $\nu_t = L_{\mathrm{RANS}}\sqrt{k} \qquad \varepsilon = C_\mu \dfrac{k_t^{3/2}}{L_{\mathrm{RANS}}} \qquad L_{\mathrm{RANS}} = \dfrac{\sqrt{k_t}}{\omega}$
- Mode LES: $\nu_t = C_1\Delta\sqrt{k} \qquad \varepsilon = C_2 \dfrac{k_t^{3/2}}{\Delta} \qquad L_{\mathrm{LES}} = C_1\Delta$

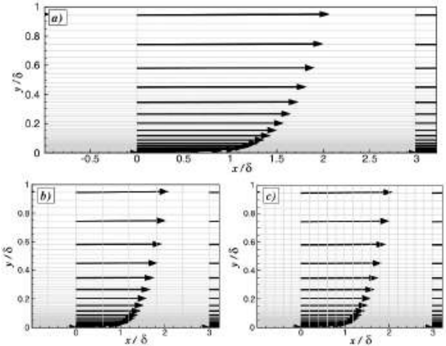
  where $C_1 = 0.06$ (from DHIT) and $C_2 = C_\mu / C_1$

Remarks:

- $L_{\mathrm{RANS}} > C_1\Delta$: mode LES; close to solid wall: mode RANS ($L_{\mathrm{RANS}} \to 0$)
- XLES close to LNS, hybrid viscosity $\Longrightarrow$ common issue of gray-area

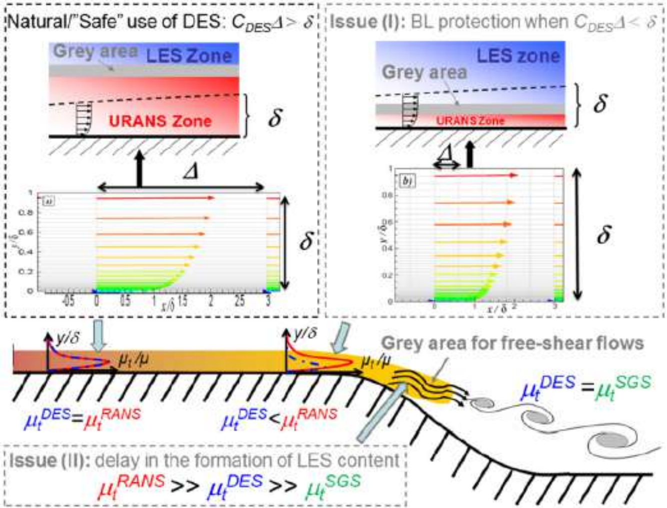
Grey area: known issues (1)

Main problem with DES: switch RANS/LES (location of the grey area) **imposed by the grid resolution!**



(a) RANS ($\Delta x > \delta$) **(c)** LES ($\Delta x < \delta$)
(b) Ambiguous spacing..

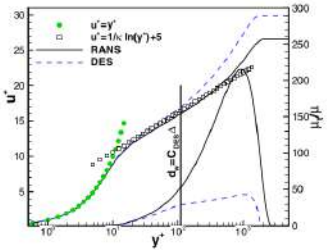
What happens in the region in which it switches from fully modelled turbulence (attached boundary layer) to mostly resolved turbulence (massive separation)?

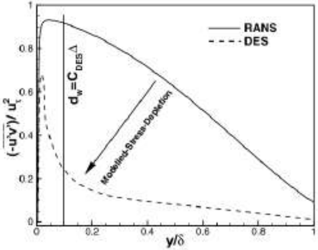


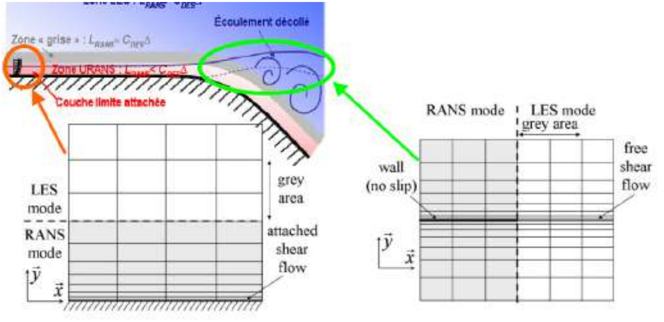
- $\mu_t \downarrow$, but not small enough to allow LES content to form
- Results in lower stresses compared to RANS: MSD + GIS

Grey area: known issues (2)

Flat plate with $C_{\mathrm{DES}}\Delta \approx 0.1\delta \Rightarrow$ Grey area at $y = 0.1\delta$







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

Issues:

- $\nu_t \downarrow$ of 75% $\Longrightarrow$ modeled stresses $\downarrow$: **Modelled-Stress-Depletion (MSD)**
- $C_f \downarrow$ of 20% w.r.t. RANS $\Longrightarrow$ Artificial relaminarization $\Longrightarrow$ premature separation (Menter et al., 2003): **Grid-Induced Separation (GIS)**

Causes:

- Insufficient resolution
- Delay of convective instabilities

Common to all global RANS/LES hybrid methods!

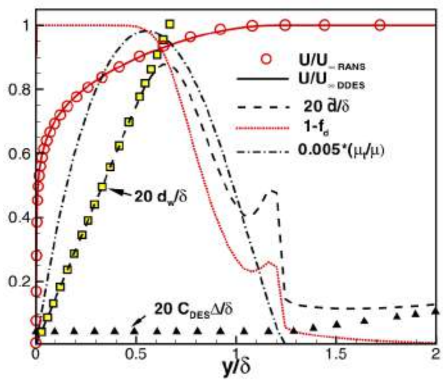
- The spatial location of the grey area is critical!
- Much attention has to be paid when defining the grid: huge constraint

Proposed modifications (I): DDES

Delayed Detached Eddy Simulation (DDES)
(Spalart et al., 2006)

Idea: modification of the lengthscale to delay the switch into LES mode through a "shielding function" f_d:

$$\tilde{d} = d_w - f_d \max(0, d_w - C_{DES}\Delta) \quad \text{with} \quad f_d = 1 - \tanh[(8r_d)^3] \quad \text{and} \quad r_d = \frac{\nu_t + \nu}{\sqrt{\frac{\partial u_i}{\partial x_j}\frac{\partial u_i}{\partial x_j}}\kappa^2 d_w^2}$$



$$f_d = \begin{cases} 0 & \text{inside B.L.} \to \text{(RANS)} \\ 1 & \text{elsewhere} \end{cases}$$

- DES97: $\tilde{d}$ depends only on the grid
- DDES: $\tilde{d}$ depends also on the local, time-dependent ν_t-field
- DDES approach can be extended to any ν_t-model with:

$$L_{DDES} = L_{RANS} - f_d \max(0, L_{RANS} - C_{DES}\Delta)$$

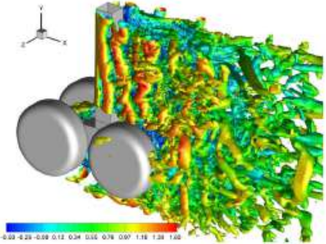
✔ The subgrid viscosity is clearly imposed far from the wall

✔ The RANS BL is well protected by the blending function f_d

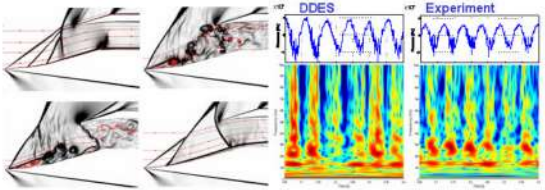
✘ No wall $\Longleftrightarrow$ no RANS behavior

Proposed modifications (I): DDES - examples

DDES of landing gear (Spalart et al., 2011)
λ_2 colored by U. Re$=10^6$, N=$7.6 \cdot 10^6$. TBL separation, vortex shedding and unsteady inter-element interaction.



Supersonic inlet buzz (Trapier et al., 2008)
Numerical schlieren, M=1.8, Re$=10^6$, N=$20 \cdot 10^6$. Large-scale self-sustained motion of the shock.

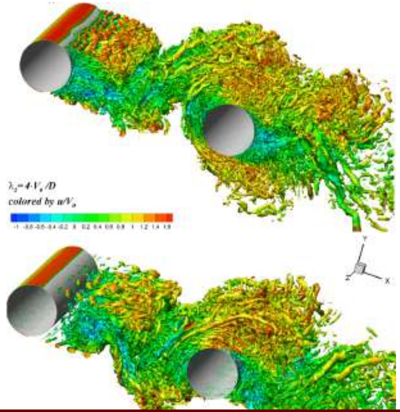


- **IDDES: Improved DDES** (Shur et al., 2008)
  bridge between Wall-Resolved and Wall-Modeled DDES

$$L_{\text{IDDES}} = \widetilde{f}_d(1+f_e)\underbrace{L_{\text{RANS}}}_{d_w} + (1-\widetilde{f}_d)\underbrace{L_{\text{LES}}}_{C_{\text{DES}}\Psi\Delta}$$

$\widetilde{f}_d$, f_e and Ψ empirical functions

IDDES (top) and DDES (bottom) of tandem cylinders
(Spalart et al., 2006) Instantaneous λ_2 colored by U. RANS separation followed by "hesitation" in shear layer



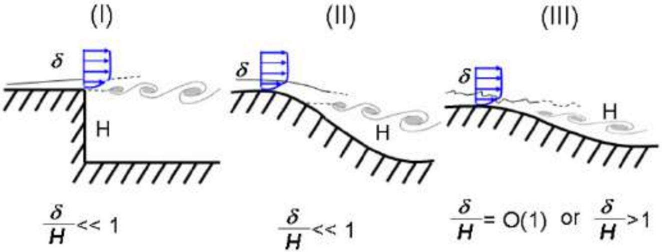
Proposed modifications (II): ZDES

Zonal Detached Eddy Simulation (ZDES)

(Deck, 2005b; Deck et al., 2011)

Idea: RANS and DES regions defined **explicitly** by the user who introduces several computational domains

- Modification of LES lengthscale and damping functions to get a faster RANS/LES switch
- Very close to pure zonal hybrid RANS/LES methods

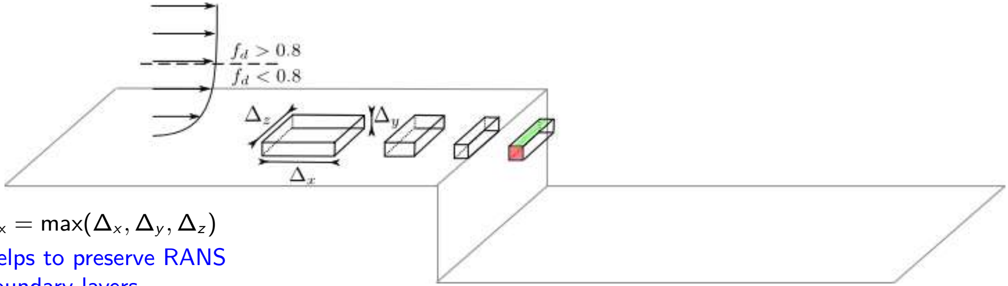


Classification of typical problems:

1. Separation fixed by the geometry (known *a priori*)
2. Separation induced by a pressure gradient on curved surface (unknown *a priori*)
3. Separation strongly influenced by the dynamics of the incoming boundary layer (Wall-Modeled LES - WMLES)

$$\tilde{d}_{\text{ZDES}} = \begin{cases} d_w & \text{if RANS zone} \\ \tilde{d}^{I}_{\text{DES}} = \min(d_w, C_{\text{DES}}\tilde{\Delta}^{I}_{\text{DES}}) & \text{if LES zone and type I} \\ \tilde{d}^{II}_{\text{DES}} = d_w - f_d \max(0, d_w - C_{\text{DES}}\tilde{\Delta}^{II}_{\text{DES}}) & \text{if LES zone and type II} \\ \tilde{d}^{III}_{\text{DES}} = \begin{cases} d_w & \text{if} \quad d_w < d_w^{\text{interf}} \\ \tilde{d}^{I}_{\text{DES}} & \text{otherwise} \end{cases} & \text{if LES zone and type III} \end{cases}$$

What is the best choice for Δ?



1. $\Delta_{\text{max}} = \max(\Delta_x, \Delta_y, \Delta_z)$
   - ✔ Helps to preserve RANS boundary-layers
   - ✘ too high in the LES zone especially in "pencil-like" cells
2. $\Delta_\omega = \sqrt{\dfrac{|\vec{\omega} \cdot \vec{S}|}{2||\vec{\omega}||}}$
   (avg. cross section of cell normal to $\vec{\omega}$)
   - ✔ suited for LES zones (allows to trigger K-H instabilities)
3. $\Delta_{\text{vol}} = \sqrt[3]{\Delta_x \Delta_y \Delta_z}$
   - ✔ suited for isotropic phenomena (or isotropic grids)

- Problems of category I: $\widetilde{\Delta}^{I}_{\text{DES}} = \Delta_{\text{vol}}$ or Δ_ω
- Problems of category II:

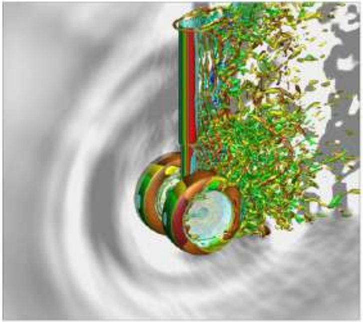
$$\widetilde{\Delta}^{II}_{\text{DES}} = \begin{cases} \Delta_{\text{max}} & \text{if} \quad f_d \leq f_{d0} \\ \Delta_{\text{vol}} \text{ or } \Delta_\omega & \text{if} \quad f_d > f_{d0} \end{cases} \qquad (f_{d0} = 0.8)$$

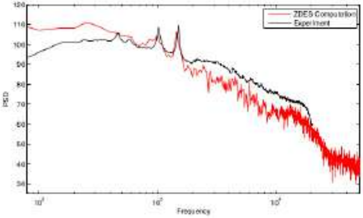
or equivalently

$$\widetilde{\Delta}^{II}_{\text{DES}} = [0.5 - \text{sign}(0.5, f_d - f_{d0})]\Delta_{\text{max}} + [0.5 + \text{sign}(0.5, f_d - f_{d0})]\Delta_\omega \text{ or } \Delta_\omega$$

Proposed modifications (II): ZDES - applications

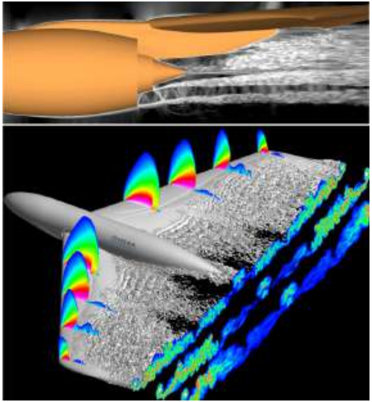
Landing gear
(Deck & Thépot, ONERA)





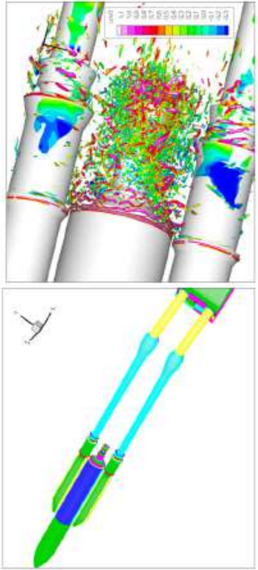
Q crit. + p' field and PSD of p'

Civil aircraft
(Brunet and Deck, 2010)



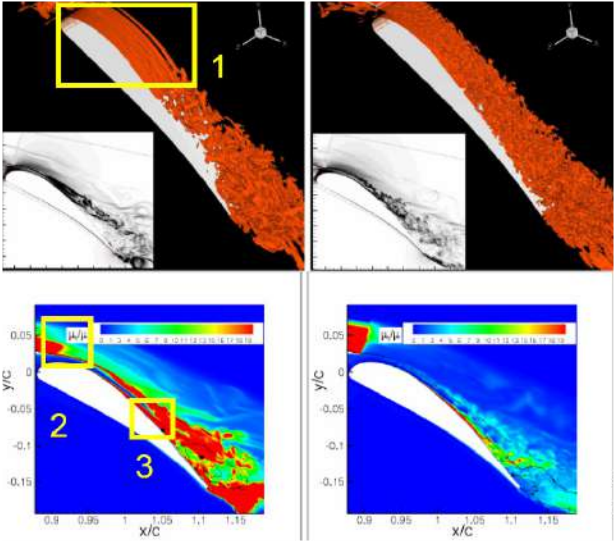
No delay in instability formation, turbulent activity well captured. $\tilde{d}^{I}_{\text{DES}}$ and $\tilde{d}^{II}_{\text{DES}}$ both used; RANS mode for B.L. on the lower side of the wing.

Ariane 5, transonic buffeting
(Deck & Thépot, ONERA)



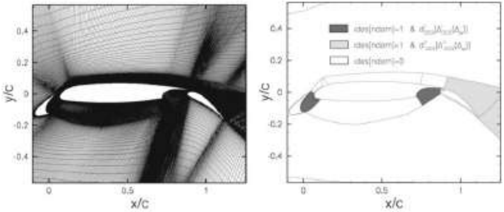
Comparison DDES / ZDES

DDES **ZDES**



Multi-element airfoil (Deck, 2012)

Large low-speed regions, strong pressure gradients, confluence of B.L. and wakes, ..



Zone 1:

- DDES: important delay, unphysical structures, poor LES content
- ZDES: no delay, physical content OK

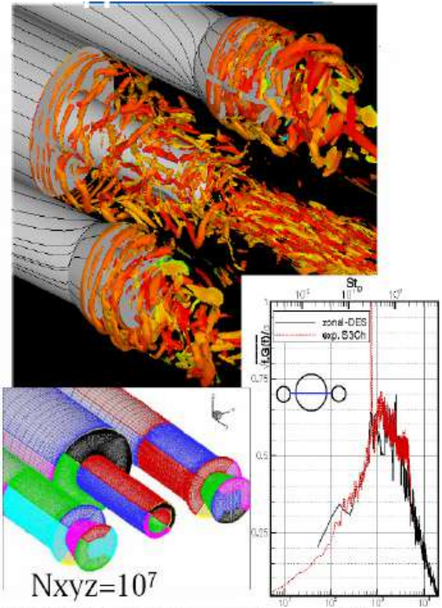
Zone 2:

- DDES: MSD?
- ZDES: OK (RANS mode)

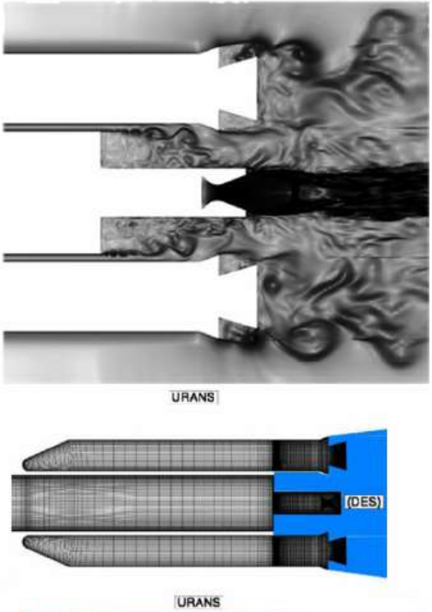
Zone 3:

- DDES: BL shielded OK
- ZDES: BL shielded OK

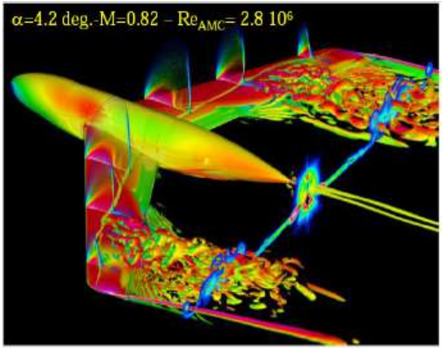
ZDES of launcher afterbody flows

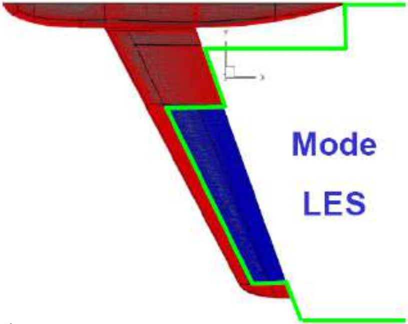


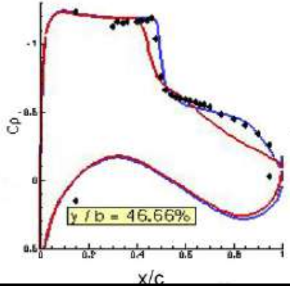
(Deck, Thépot, Thorigny 2007)

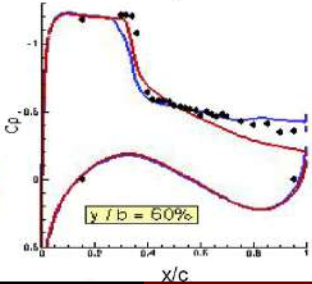


ZDES of transonic buffet







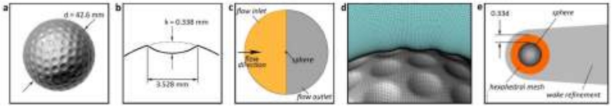


Blue : mode LES

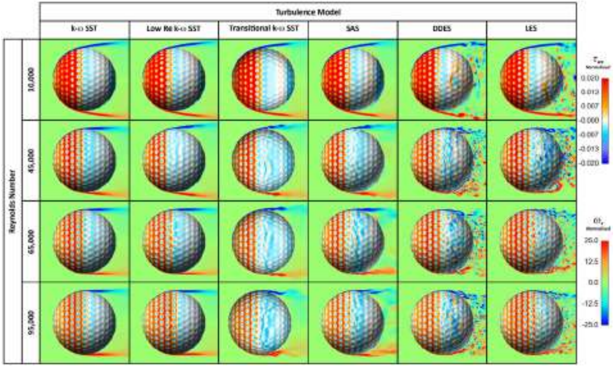
Red : mode URANS

(Brunet, Deck 2007)

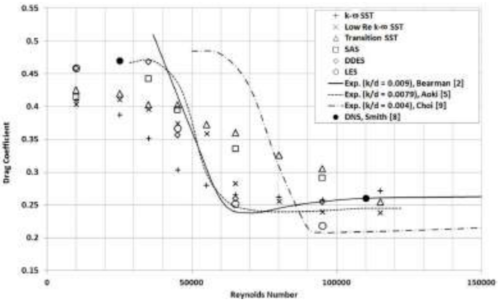
Dimpled sphere



Turbulence Model	Model Family	Notes
k-ω SST	URANS	Shear Stress Transport formulation [16]
Low Re k-ω SST	URANS	Inclusion of the Wilcox low Reynolds number terms [*]
Transition SST	URANS	SST with inclusion of equations for Intermittency and transition onset criteria
SAS – Scale Adaptive Simulation	SRS – URANS	Coupled with Transition SST for near wall flow
DDES – Delayed Detached Eddy Simulation	SRS – URANS	Coupled with k-ω SST Low Re for near wall flow
LES (WALE) – Large Eddy Simulation	SRS	WALE – Wall Adapting Local Eddy Viscosity Model



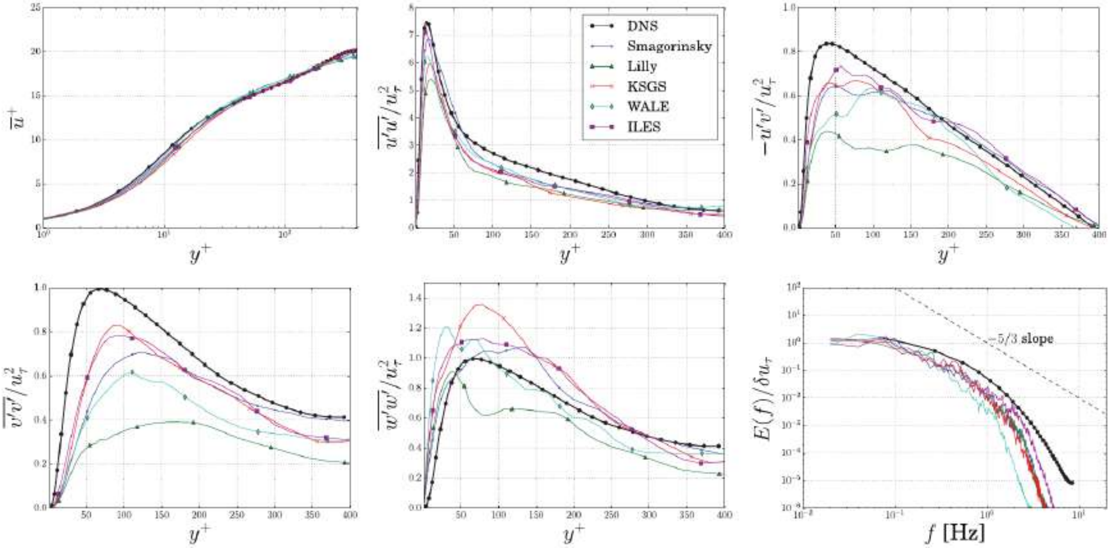
Hart (2016)



- DDES good w.r.t. LES
- URANS fails to accurately predict time-dependent features as dimple shear layers and large-scale shedding of wakes

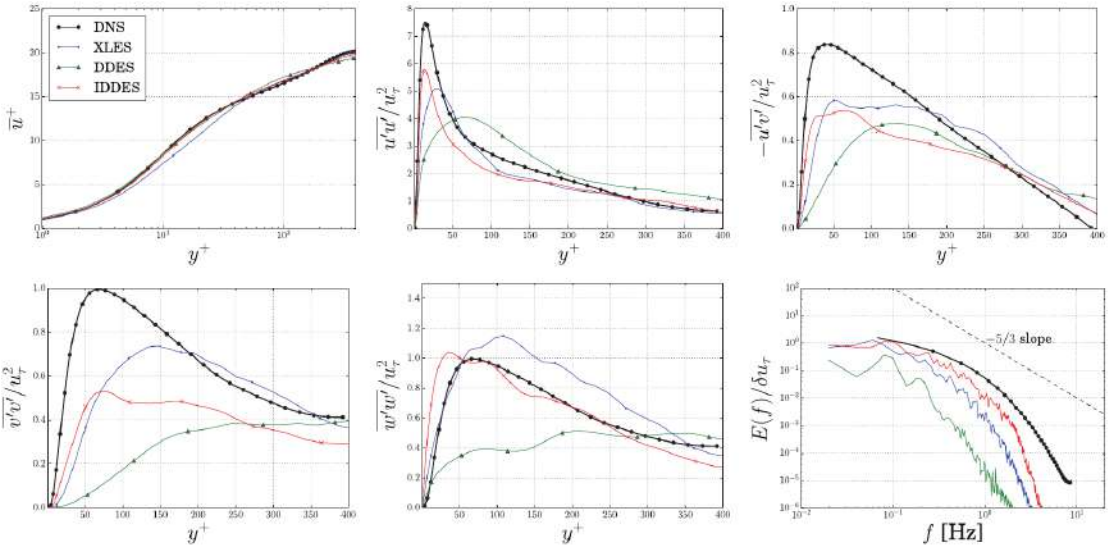
Channel flow comparison - LES

Klapwijk et al. (2020)



Channel flow comparison - Hybrid RANS/LES

Klapwijk et al. (2020)



1 Introduction

2 Statistical approaches

3 Global approaches

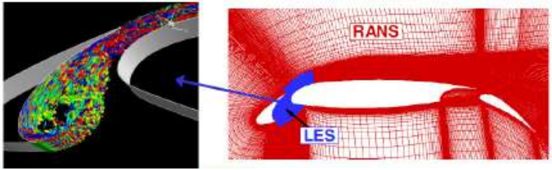
4 Zonal approaches

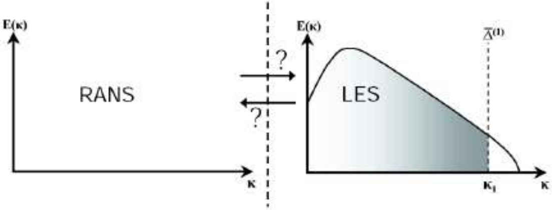
5 Conclusion

Zonal RANS/LES: motivations

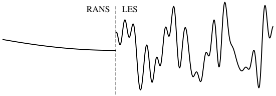
Principle of zonal approaches:

- Regions resolved imposing a priori RANS or LES
- The user adds LES regions where RANS is not efficient or where a finer description is required
  - Multiblock partitioning of the domain
- Need a good knowledge of the flow physics

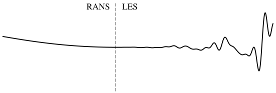




- Spatial/spectral discontinuity of the solution
- Multiresolution problem at the interface



What we want

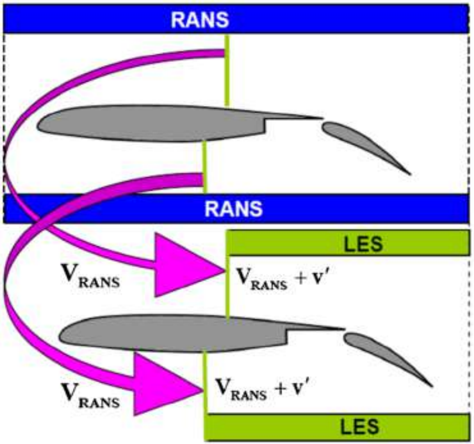


What we have

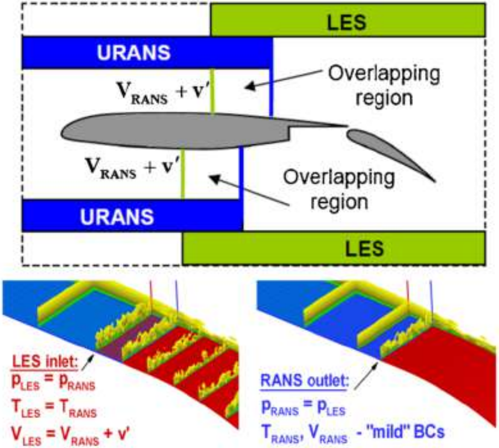
- RANS/LES large adaptation distance
- Very active research topic

RANS/LES coupling

Two-stage (one-way coupled)



One-stage (fully-coupled)



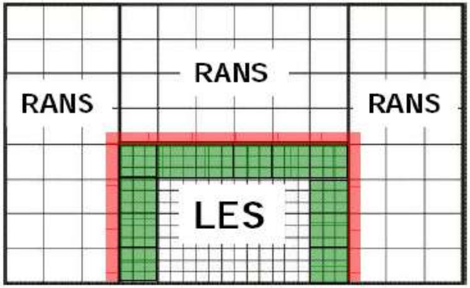
Full variables approach - Communications I

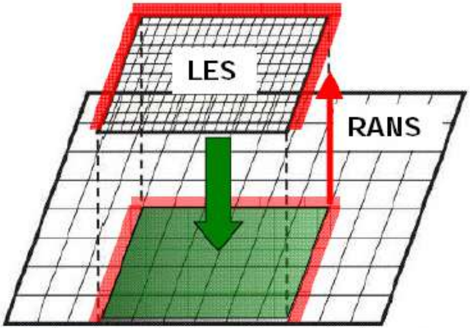
Appropriate boundary conditions have to be defined for the LES and RANS domains

Numerical operators have to be defined to switch from a LES description to a RANS one, and vice versa

- Transfer **LES** $\rightarrow$ **RANS**: loss of information, referred to as **restriction**
- Transfer **RANS** $\rightarrow$ **LES**: turbulent content to be generated, referred to as **enrichment**

In the case of one-stage coupling, the LES domain may overlap an entire region of the RANS domain $\Longrightarrow$ restriction applied everywhere in the overlapped region!





Full variables approach - Communications II

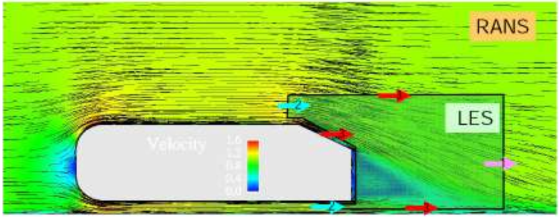
Restriction procedure: LES → RANS

Aim: mimic the application of a statistical averaging operator. In practice, use a spatio-temporal average:

$$\bar{u}_{\text{RANS}} \simeq \langle \bar{u}_{\text{LES}} \rangle_{\Omega, T}$$

Switch from resolved turbulent fluctuations to a statistical turbulence description:

- Remove turbulent flucts. from aerodynamic field
- Need to reconstruct statistical turbulence quantities (k, ε, ν_t, ...)



Enrichment procedure: RANS → LES

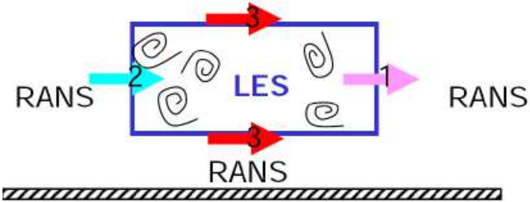
Aim: provide B.C. for the LES domain

$$\bar{u}_{\text{LES}} = \mathcal{I}\{\bar{u}_{\text{RANS}}\} + \delta u$$

mean value interpolated + turbulent fluctuation

Types of interfaces based on mean velocity normal to interface:

1. LES outflow
2. LES inflow
3. Tangential interface (combination of 1 & 2) LES outflow as basis for tangential coupling

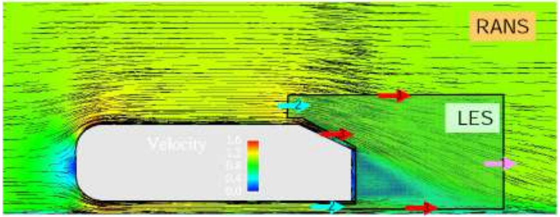


RANS → LES coupling

Cases 1 and 3: lateral coupling / outflow

Several strategies depending on the turbulence level at the interface:

- Low: no fluctuation added + non-reflecting treatment for compressible flows
- Medium: computed in the LES domain and extrapolated at the interface
- High: use specific reconstruction techniques similar to those for inflow conditions



Case 2: inflow

- Laminar inflow: no fluctuation added + non-reflecting treatment for compressible flows
- Turbulent inflow: hot topic
  - Main test case: inflow for TBL simulations

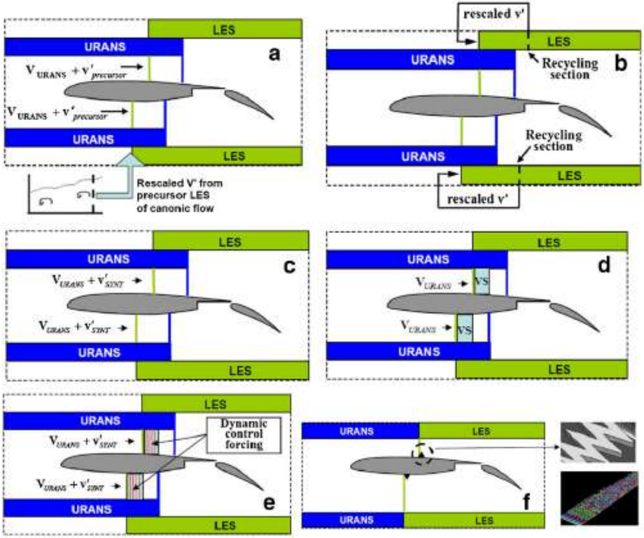
Without appropriate perturbations at the LES inflow:

- Reaction of a buffer zone (re-generation of realistic turbulence) generally of too large extent
  - problem similar to the “grey area”
- Artificial laminarization
- Artificial separation
- Boundary layers too thin
- ...

Problem common with DNS / LES Methods

Generation of LES unsteady content

Large-Eddy Stimulation (Batten et al., 2004)



(a) Precursor DNS or LES

(b) Turbulence recycling

- Spalart's rescaling method (Spalart, 1988)
- Rescaling/recycling method (Lund et al., 1998)
- POD/LSE inflow from experiments (Druault et al., 2004; Johansson and Andersson, 2004)

(c) Synthetic turbulence

- Inverse Fourier transform (Lee et al., 1992)
- Randomization of frozen turbulence (Na and Moin, 1998)
- Lifted streaks and 3-D vortices (Sandham et al., 2003)
- Digital filtering procedure (Klein et al., 2003)
- Random Fourier Modes (Kraichnan, 1970; Davidson and Billson, 2006)
- Synthetic Eddy Method (Jarrin et al., 2006; Pamiès et al., 2009)

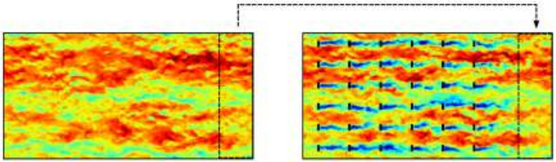
(d) Volume source terms

(e) Dynamic control forcing

(f) Vortex generating devices

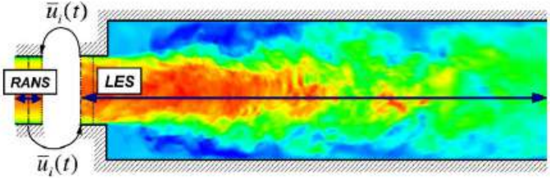
Precursor simulations

Idea: Retrieving inlet data from precursor simulation

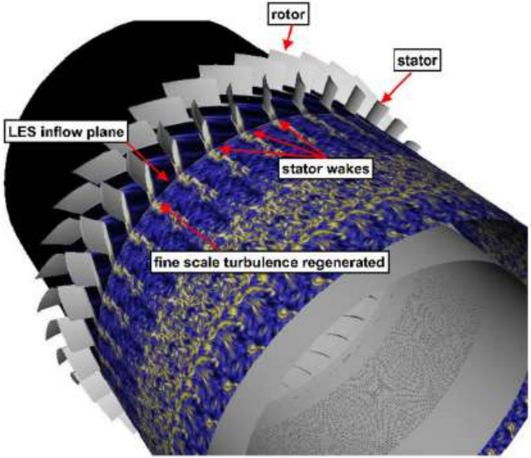


Munters et al. (2016)

Schlüter et al. (2004)



Schlüter et al. (2005)



✔ Requires very few assumptions

✔ "Adjustment" zone not needed

✘ Expensive and a lot of I/O

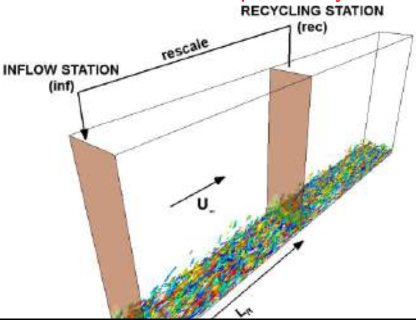
- Sometimes interpolation in time used

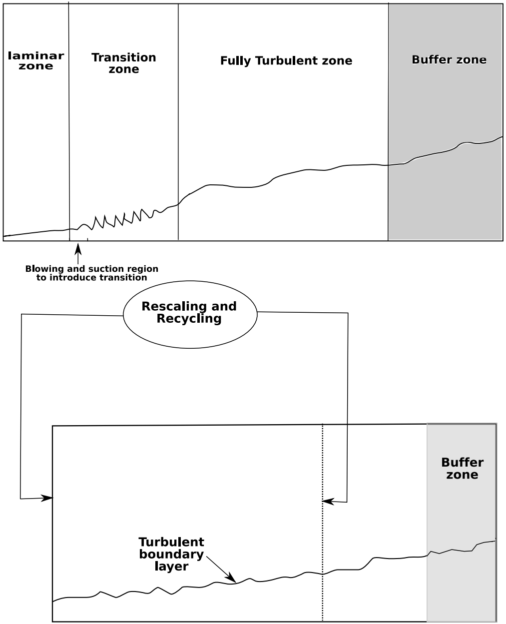
✘ No feedback to the precursor

Rescaling and Recycling methods

Idea (Spalart, 1988; Lund et al., 1998): Take a plane from a location downstream, rescale the data and reintroduce at the inflow

- ✔ Simple and easy to implement
- ✘ Scaling laws must hold
- ✘ Limited to fully-turbulent, self-similar configurations
- ✘ How to initiate the recycling process?
- ✘ Introduction of a non-physical low-frequency $\frac{U_{\text{conv}}}{L_{\text{rec}}}$ due to artificial streamwise periodicity



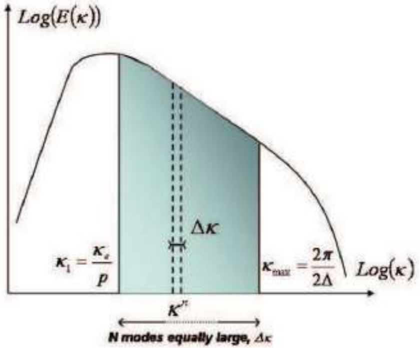


Synthetic turbulence: RFM - Random Fourier modes (Kraichnan, 1970)

- **Idea**: Superimpose random synthetic flucts. to mean field
- Hyp.: turbulence can be specified by using only low-order stats
- The fluctuating velocity field is expressed as a Fourier series with N **independent RFM modes:**

$$\vec{u}'(\vec{x},t) = \sum_{n=1}^{N} 2\hat{u}_n \cos(\vec{k}_n.(\vec{x}-\overline{\vec{u}}t)+\omega_n t+\psi_n)\vec{a}_n$$

  - ψ_n, $\vec{k}_n$, $\vec{a}_n$ random variables with given p.d.f.s;
  - an unfrozen turbulent field is obtained by incorporating the convection velocity $\overline{\vec{u}}$ and the pulsation $\omega_n = 2\pi u' k_n$
  - amplitudes $\hat{u}_n$ determined from a turbulent energy spectrum



Turbulent energy spectrum $E(k)$: von Kármán model

$$\hat{u}_n = \sqrt{2E(k_n)\Delta k_n} \quad \text{with} \quad E(k) = \alpha_1 \frac{u'^2}{k_e} \frac{(k/k_e)^4}{\left[1+(k/k_e)^2\right]^{17/6}},$$

with logarithmic distribution of the N modes

$$k_n = \exp\left[\ln k_1 + (n-1)\Delta k\right]$$

with $n = 1,..,N$ and $\Delta k = (\ln k_{max} - \ln k_{min})/(N-1)$

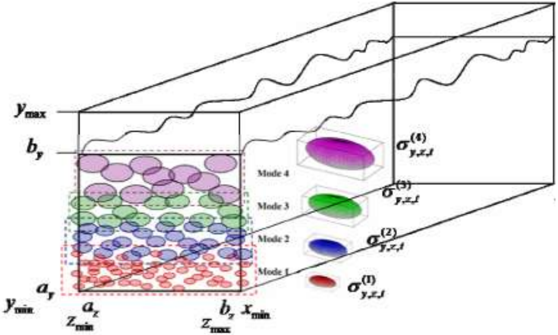
Parameters:

- $k_{min} = 1/\delta$, $k_{max} = 100/\delta$, and $N = 100$
- anisotropy: method of Smirnov et al. (2001)

Synthetic turbulence: SEM - Synthetic Eddy Method (Jarrin et al., 2006)

- Wall-bounded flows populated with eddies whose sizes depend on distance from the wall
- **Idea**: random superimposition of Gaussian-type spots
- A signal $\widetilde{u}_j$ is written as the sum of P modes $\widetilde{v}_{jp}$, each one resulting from the sum of $N(p)$ structures:

$$\widetilde{u}_j = \sum_{p=1}^{P} \widetilde{v}_j p = \sum_{p=1}^{P} \frac{1}{\sqrt{N(p)}} \times \sum_{k=1}^{N(p)} \epsilon_k \Xi_{jp}\left(\frac{t - t_k - l_p^t}{l_p^t}\right) \Phi_{jp}\left(\frac{y - y_k}{l_p^y}\right) \Psi_{jp}\left(\frac{z - z_k}{l_p^z}\right)$$



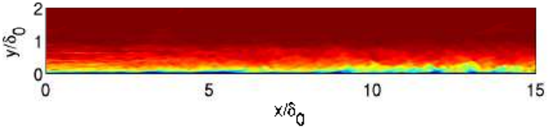
(Pamiès et al., 2009)

- $N(p)$ number of structures
- $\epsilon_k \pm 1$ random sign for each structure k
- t_k random instant for the birth of the structure k
- (y_k, z_k) random location of the center of the structure k
- $\Xi_{jp}(\widetilde{t}) \times \Phi_{jp}(\widetilde{y}) \times \Psi_{jp}(\widetilde{z})$ shape function over $[-1, 1]^3$
- ℓ_p^y, ℓ_p^z wall-normal and spanwise length-scales
- $\ell_p^t = \ell_p^x / c^p$ longitudinal time-scale deduced from longitudinal length-scale and convection velocity

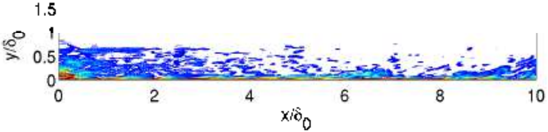
Comparison of synthetic inflow methods

Random Fourier Modes

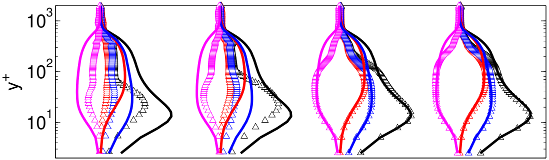
Streamwise velocity



Vorticity

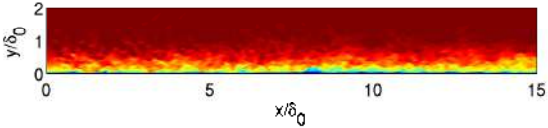


Evolution of *rms* profiles at x/δ_0 =3, 5, 10, 15

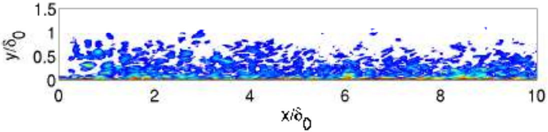


Synthetic Eddy Method

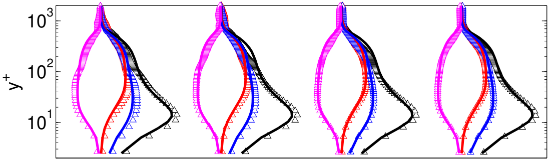
Streamwise velocity



Vorticity



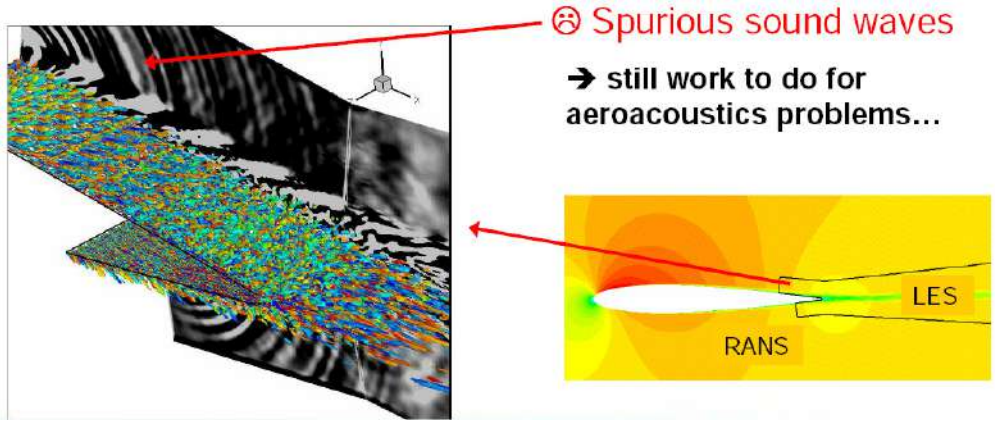
Evolution of *rms* profiles at x/δ_0 =3, 5, 10, 15



Turbulent inflow for LES: synthetic turbulence

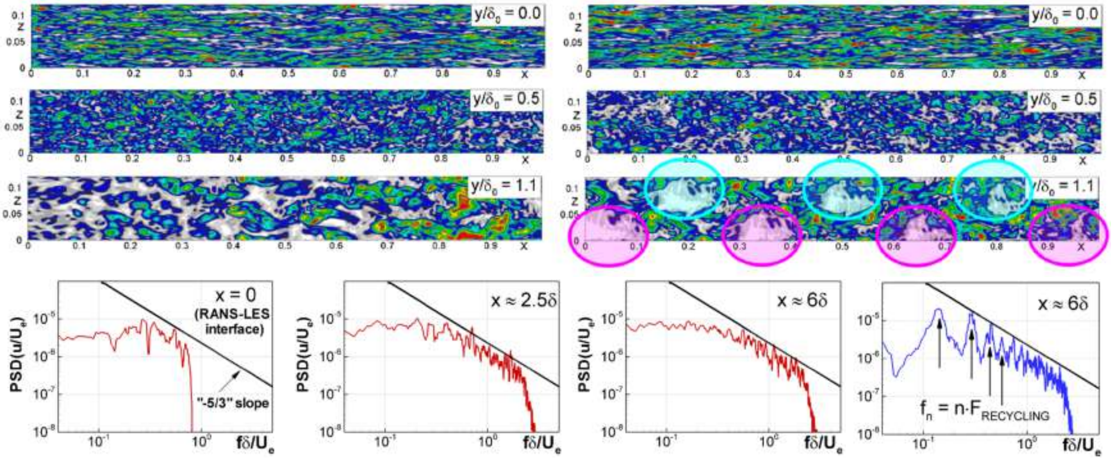
- For a correct coupling, the synthetic turbulence must satisfy the mean properties given by the RANS computation (k_t, ε, τ_{ij}^R, length and time scales of the large structures,..)
- Several methods make it possible to consider turbulent inflow conditions
- Efficient from the pure aerodynamic point of view
- .. But still significant generation of spurious noise

Flow at the trailing edge of a NACA0012 airfoil



Comparison

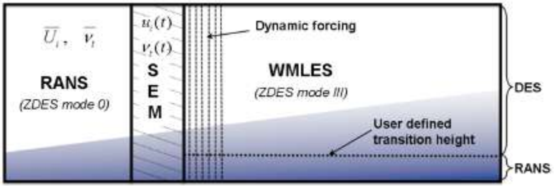
Shur et al. (2014): Zonal RANS-IDDES with STG (left) and IDDES with recycling (right)



Artificial Forcing

Volume source term

- ✔ Continuous velocity field w.r.t. STG
- ✔ Potentially good for AA due to smooth transition
- ✘ Only tested on 1 cell (i.e., equiv to STG)



Dynamic (closed-loop) control forcing

- ✘ Long adaptation region

Vortex generating device

- ✔ Low cost, simple implementation
- ✔ "Quiet" (ok for AA)
- ✘ Long adaptation region
- ✘ Choosing the optimal shape not easy

1 Introduction

2 Statistical approaches

3 Global approaches

4 Zonal approaches

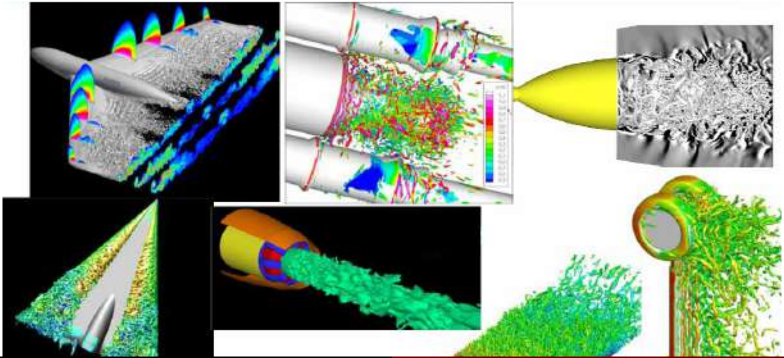
5 Conclusion

General models evaluation (I)

Guideline for using these method for industrial turbulent flow modelling

Introduction of three flow categories for which steady state calculations are not sufficient:

1. **Category I**: flow characterized by scale separation between unsteadiness of mean field and turbulence
   - Small-amplitude forced oscillation of a vehicle, flow around helicopter blades, ...
2. **Category II**: Massively separated flows characterized by a large scale unsteadiness dominating the time-averaged solution:
   - Flow behind a car, airfoil at high angle of attack, downwind side of buildings..
3. **Category III**: Flow sensitive to the Lagrangian history of the upstream / free-stream turbulence:
   - Shallow separation bubble, confluence of thin layers



General models evaluation (II)

Family	Method	Formulation	RANS/LES interface	Flows I	Flows II	Flows III
Unsteady statistical approaches $\nu_t = \nu_t(L_{\text{RANS}})$	URANS, PANS	Same turb. model as in RANS	/	$+$	$-$?	$-$
	SDM *(Minh, 1999)* OES *(Braza, 2000)*	Turbulence model modified $\nu_t^{\text{SDM}} < \nu_t^{\text{RANS}}$	/	/	$+$?	$-$
	TRRANS *(Travin et al., 2004)*	$\varepsilon_{\text{TRRANS}} = \varepsilon_{\text{RANS}} \cdot F_{\text{TTRANS}}$ $F_{\text{TRRANS}} = \max\left[\left(\frac{S}{c_{\text{TRANS}}\Omega}\right)^2, 1\right]$	no clear border	$+$	$+$?	$-$
	SAS *(Menter and Egorov, 2010)*	Turbulent length scale sensitized to L_{vK}	no clear border	$+$	$+$?	$-$
Global hybrid methods $\nu_t = \nu_t(L_{\text{RANS}}, \Delta)$	VLES (FSM) (Speziale, 1998)	$\nu_t = \alpha\nu_t^{\text{RANS}}$ $0 \leq \alpha\left(\frac{L_\Delta}{L_k}\right) \leq 1$	no clear border	$+\sim$	$+$	$-$
	LNS *(Batten et al., 2002)*	$\alpha = \min\left[\frac{\nu_t^{\text{LES}}}{\nu_t^{\text{RANS}} + \epsilon}, 1\right]$	flow-dependent	$+\sim$	$+$	$-$
	Blending methods *(Baurle et al., 2003)*	$\nu_t = \Gamma\nu_t^{\text{RANS}} + (1-\Gamma)\nu_t^{\text{LES}}$ $\Gamma = \Gamma(L_\Delta / L_{\text{RANS}})$	flow-dependent	$+\sim$	$+$	$-$

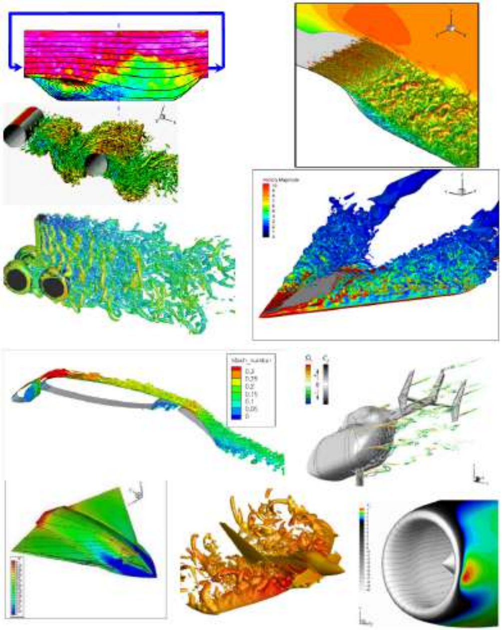
General models evaluation (III)

Family		Method	Formulation	RANS/LES interface	Flows I	Flows II	Flows III
Global hybrid methods $\nu_t = \nu_t(L_{\mathrm{RANS}}, \Delta)$	**DES type**	DES *(Spalart, 1997)* *(Strelets, 2001)*	$\nu_t = \mathcal{U} \times \mathcal{L}$ $\mathcal{L} = \min(L_{\mathrm{RANS}}, L_\Delta)$	fixed (SA-DES) flow-dependent (SST-DES)	$+\sim$	$+$	$-$
		XLES *(Kok et al., 2004)*	similar to DES, DES limiter applied to all turbulent variables	flow-dependent	$+\sim$	$+$	$-$
		DDES *(Spalart et al., 2006)* *(Shur et al., 2008)*	$\mathcal{L} = L_{\mathrm{RANS}} - f_d \max(0, L_{\mathrm{RANS}} - L_\Delta)$ $f_d = \begin{cases} 0 & \forall L_\Delta \text{ in the TBL} \\ 1 & \text{in LES regions} \end{cases}$	flow-dependent	$+\sim$	$+$	$-$
		ZDES *(Deck, 2005a)* (Deck et al., 2011)	$\mathcal{L} = (1 - \mathrm{id[ndom]})L_{\mathrm{RANS}} + \mathrm{id[ndom]} \cdot \tilde{L}_{\mathrm{DES}}^{\mathrm{I,\ II\ or\ III}}$ $\mathrm{id[ndom]} = \begin{cases} 0 \text{ in RANS mode (def.)} \\ 1 \text{ in LES mode} \end{cases}$ $\tilde{L}_{\mathrm{DES}}^{\mathrm{I,\ II\ or\ III}}$ chosen according to the pb.	fixed or flow-dependent	$+\sim$	$+$	$+$
Zonal hybrid methods		RANS/LES coupling Wall-Modelled LES NLDE, ZDES (mode III)	Models applied separately LES content at the interface explicitly reconstructed	fixed	$-\sim$	$+\sim$	$+$

from *Multiscale & Multiresolution approaches for turbulence*, Sagaut, Deck & Terracol, Imperial College Press, 2013

Concluding remarks

- RANS Modeling is:
  - Less elegant than we would like
  - More useful than ever
- Progress is held back by:
  - Lack of new ideas that work
  - Difficulty in improving a model on enough "fronts" at once
  - Low tolerance for complex equations
  - Lack of perfect, detailed experiments
  - Lack of complex-flow, high-Reynolds-number DNS
  - Lack of perfect CFD (grid convergence)
- Careful prediction or prescription of transition is delicate
- RANS is a partner with LES
  - Hybrid methods are here to stay
  - They keep their promises
  - Not "push-button" methods! User burden is high
  - Zonal and non-zonal hybrid methods will both grow



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