Detached Eddy Simulation of Flows Over Rough Surfaces

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Motivation and objectives

- Many flows are over rough surfaces — $k^+ \gtrsim 5$;
  wind flow is usually in the fully rough regime — $k^+ \gtrsim 70$
- Traditional approach: wall-model based on equilibrium
  $\Rightarrow$ not accurate for flows with separation

- Consider non-equilibrium effects: pressure gradient, curvature, ...
- Improve prediction of separation
- Verify improvement over RANS

Work sponsored by the Portuguese Foundation for Science and Technology (FCT), under grant SFRH/BPD/5674/2001.

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Cases studied

Flat surface:

- $Re_{\theta_{ref}} = 1\,700$
- Domain size: $325\theta_{ref} \times 50\theta_{ref} \times 50\theta_{ref}$
- Sand-grain roughness: $k^+ = 70$

Wavy surface:

- $Re_\delta = 410\,000$
- Domain size: $2\lambda \times \lambda \times 2\lambda$
- Sand-grain roughness: $k^+ = 520$

Experiments: Acharya, Bornstein and Escudier, 1998, and Gong, Taylor and Dornbrack, 1996.

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Mathematical model

- Incompressible flow with constant properties
- Filtered continuity and Navier-Stokes equations
- Finite volume approach, non-staggered grid, curvilinear coordinates
- Spatial discretisation: second-order centred finite differences
- Temporal discretisation: fractional-step with Adams-Bashfort and Crank-Nicholson

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Boundary conditions

Flat surface:

- Inlet: re-scaling technique (Lund *et al.*, 1998) — boundary layer with $\theta = \theta_{\text{ref}}$
- Outlet: convective condition $\partial\overline{u}_i/\partial t + U_b\,\partial\overline{u}_i/\partial x = 0$

Wavy surface:

- Streamwise: periodic
- Wall: no slip
- Top: free-slip
- Spanwise: periodic

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Detached Eddy Simulation

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\tilde{S}\tilde{\nu} + \frac{1}{\sigma}\left\{\nabla\cdot\left[\left(\nu+\tilde{\nu}\right)\nabla\tilde{\nu}\right] + c_{b2}\left(\nabla\tilde{\nu}\right)^2\right\} - c_{w1}\, f_w \left[\frac{\tilde{\nu}}{\tilde{d}}\right]^2$$

$$\begin{aligned}
\nu_{\rm t} &= \tilde{\nu} f_{v1}\\
\tilde{d} &= \min(d, C_{\rm DES}\Delta)\\
d &= \text{distance to the nearest wall} + \text{roughness length}\\
\Delta &= \max(\Delta x, \Delta y, \Delta z)
\end{aligned}$$

Detached Eddy Simulation

Boeing variant

- Roughness length: $d_0 = \exp\left(-8.5\kappa\right) k$
- Boundary condition: $\dfrac{\partial \widetilde{\nu}}{\partial n} = \dfrac{\widetilde{\nu}}{d}$

ONERA variant

- Roughness length: $\dfrac{\widetilde{\nu}_w}{\kappa \cdot u_\tau}$
- Boundary condition: $\widetilde{\nu}_w^+ = \mathrm{f}\left(k^+\right)$ $\Rightarrow \widetilde{\nu}_w$ *depends of* u_τ

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Grids

Flat surface

Nodes	$\Delta x/\theta_{ref}$, $\Delta z/\theta_{ref}$	$\Delta y_{min}/\theta_{ref}$
$597 \times 132 \times 102$	0.5	0.016

Wavy surface

Nodes	$\Delta x/\lambda$, $\Delta z/\lambda$	$\Delta y_{min}/\lambda$
$228 \times 138 \times 228$	8.8×10^{-3}	5.7×10^{-5}

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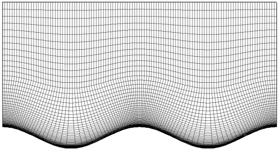
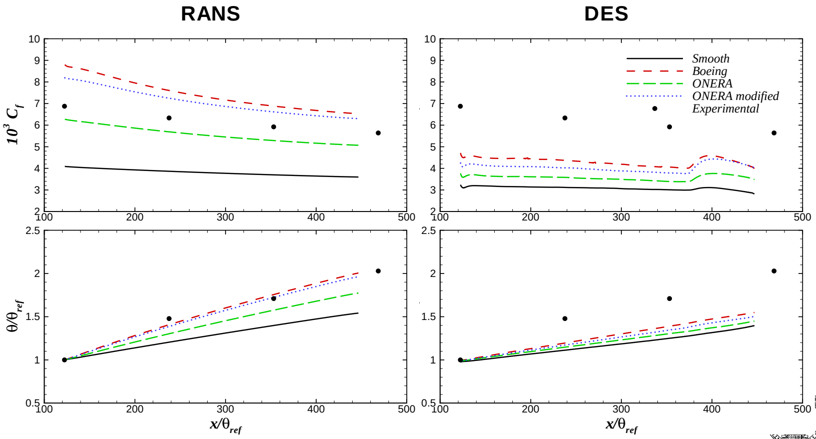
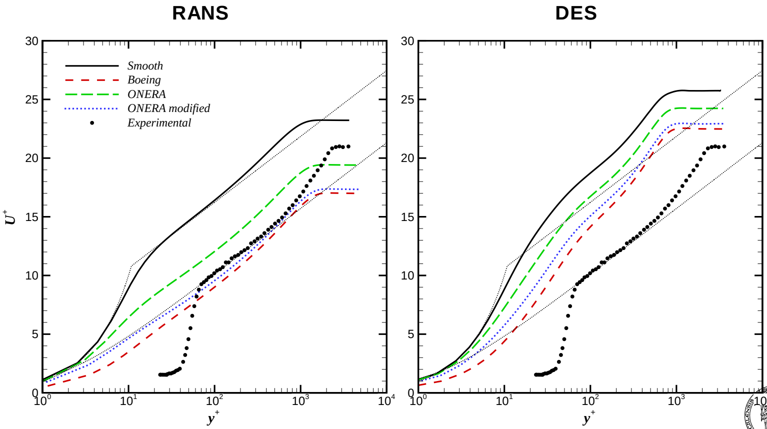


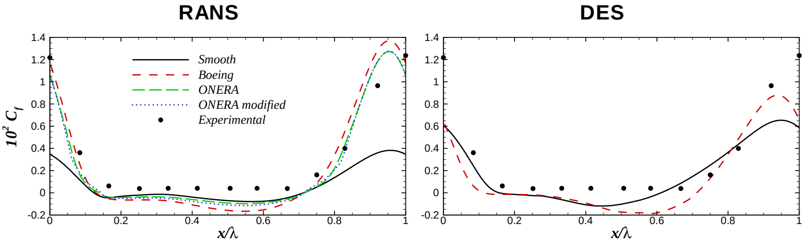
Flat surface: friction and momentum thickness



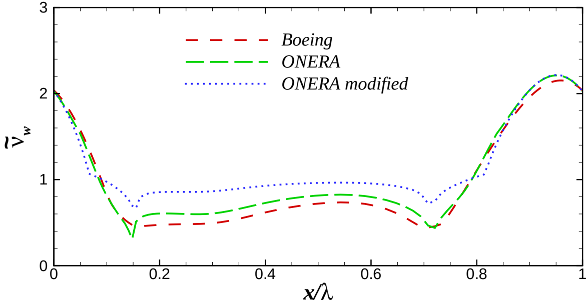
Flat surface: mean velocity profiles



Wavy surface: friction coefficient



Wavy surface: RANS wall eddy viscosity



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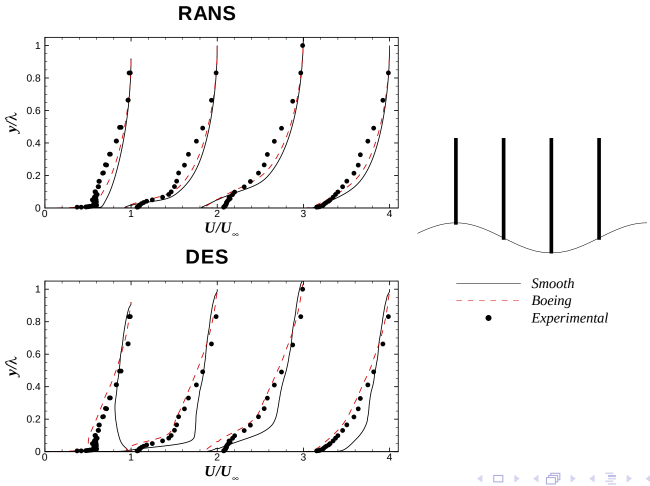
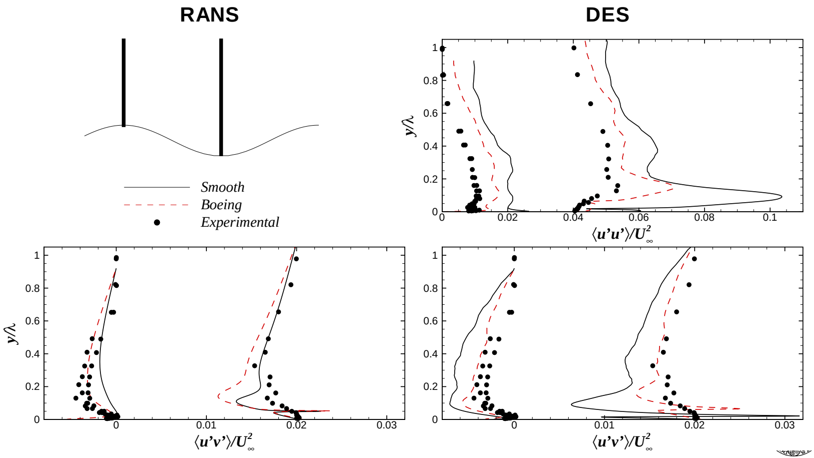
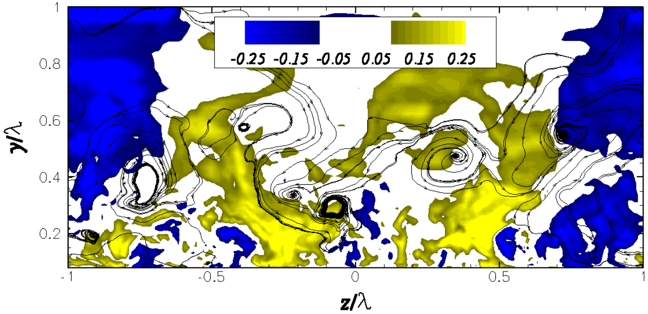


Wavy surface: Reynolds stresses



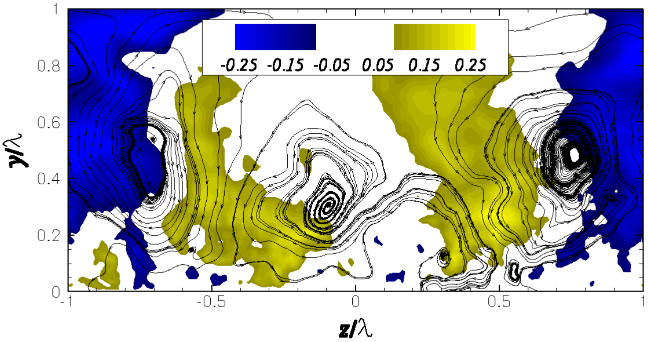
Wavy surface

Instantaneous secondary flow streamlines over streamwise velocity fluctuation ($x/\lambda = 0$)



Wavy surface

Coherent secondary flow streamlines over coherent streamwise velocity — $\widetilde{u}_i = \overline{u_i - \langle U_i \rangle}$



Conclusions

- DES showed larger errors in the friction for rough surface than for smooth surface
- ONERA variant could not be used in DES of flow with separation, due to instability caused by peaks in wall viscosity at separation and reattachment
- DES predicted the “jet” above the crest, RANS did not
- DES predicted streamwise vortices
- Coherent velocity induced by streamwise vortices was very small and overwhelmed by turbulent fluctuations