Two-equation hybrid RANS-LES Models: A novel way to treat k and ω at the inlet [2]

Lars Davidson

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Research Question

1. I want to use a $k-\omega$ DES model
   1.1 How do I prescribe inlet values on k and ω?
   1.2 What about the URANS region? Should I prescribe k and ω from a steady RANS solution?
2. The proposed method is to add commutation terms in the k and ω equations.
3. The commutation terms read (Δ goes from Δ_{RANS} to Δ_{LES})

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4. The method can also be used in embedded LES (i.e. at the RANS-LES interface)

The Zonal $k-\omega$ Hybrid RANS-LES PDH Model

- In the LES region, the model reads

$$
\begin{aligned}
\frac{\partial k}{\partial t} + \frac{\partial \bar{v}_i k}{\partial x_i} &= P^k - f_k \frac{k^{3/2}}{\ell_t} + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \\
\frac{\partial \omega}{\partial t} + \frac{\partial \bar{v}_i \omega}{\partial x_i} &= C_{\omega_1} f_\omega \frac{\omega}{k} P^k - C_{\omega 2}\omega^2 + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + C_\omega \frac{\nu_t}{k}\frac{\partial k}{\partial x_j}
\end{aligned}
$$

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\nu_t = f_\mu \frac{k}{\omega}, \quad P^k = \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\frac{\partial \bar{u}_i}{\partial x_j}, \quad \ell_t = C_{LES}\Delta_{dw}
$$

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\Delta_{dw} = \min\left(\max\left[C_{dw} d_w, C_w \Delta_{max}, \Delta_{nstep}\right], \Delta_{max}\right)
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- In the RANS regions, $\ell_t = k^{1/2}/(C_k\omega)$.
- The interface between LES and RANS regions is chosen at a fixed grid line ($y^+ \simeq 500$)

Varying filter size

- When filter size in LES varies in space, an additional term appears in the momentum equation.
- The reason? the spatial derivatives and the filtering do not commute.
- For the convective term in Navier-Stokes, for example, we get

$$\overline{\frac{\partial v_i v_j}{\partial x_j}} = \frac{\partial}{\partial x_j}(\overline{v_i v_j}) + \mathcal{O}\left((\Delta x)^2\right)$$

- Ghosal & Moin [4] showed that the error is proportional to $(\Delta x)^2$; hence it is usually neglected.

Commutation error in k equation

- In zonal[1] hybrid RANS-LES, the length scale at the RANS-LES interface changes abruptly from a RANS length scale to a LES length scale.
- Hamda [5] found that the commutation error at RANS-LES interfaces is large.
- For the k equation the commutation term reads

$$\overline{\frac{\partial u_i k}{\partial x_i}} = \frac{\partial \bar{u}_i k}{\partial x_i} - \frac{\partial \Delta}{\partial x_i}\frac{\partial \bar{u}_i k}{\partial \Delta}$$

[1]the interface is chosen at a location where the RANS and LES length scales differ

Commutation term: physical meaning

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- The filterwidth decreases across the interface, i.e. $\partial \Delta / \partial x_1 < 0$
- k decreases when going from RANS to LES $\Rightarrow$ $\partial \bar{u}_1 k / \partial \Delta = \underbrace{(k_{LES} - k_{RANS})}_{<0} / \underbrace{(\Delta_{LES} - \Delta_{RANS})}_{<0} > 0$

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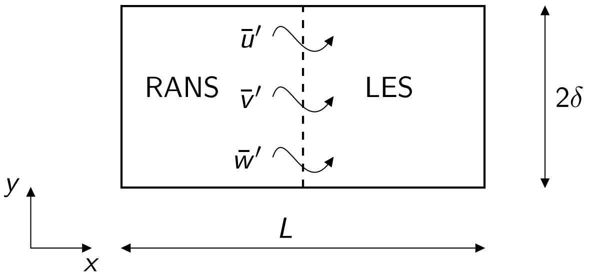
- $\Rightarrow$ The commutation term > 0
- $\Rightarrow$ The commutation term < 0 on the right-side of the k equation.
- Hence, the commutation term at the RANS-LES interface reduces k.

Commutation term at the RANS-LES interface



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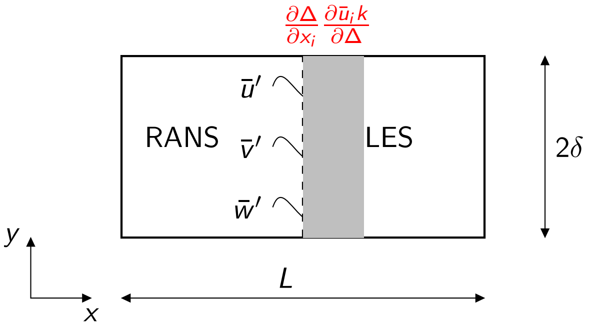
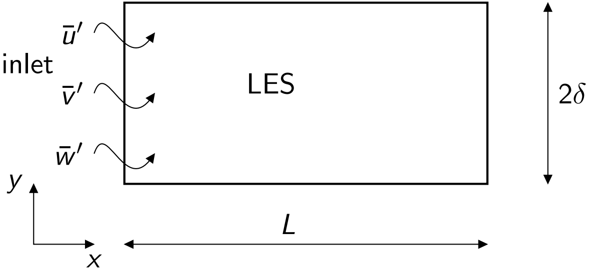
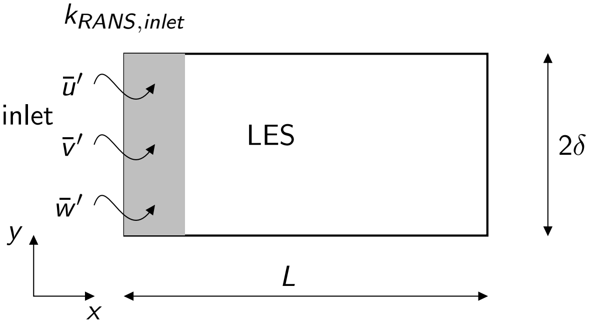


Commutation term at the LES inlet



Commutation term at the LES inlet

$$\frac{\partial \Delta}{\partial x_i} \frac{\partial \bar{u}_i k}{\partial \Delta}$$



Commutation term in the ω equation

- Let us start by looking at the ε equation.
  - What happens with ε when a fluid particle moves from a RANS region into an LES region?
  - The answer is, nothing. The dissipation is the same in a RANS region as in an LES region.
- Transformation of the k and ε equations to an ω equation gives

$$\frac{d\omega}{dt} = \frac{d}{dt}\left(\frac{\varepsilon}{C_k k}\right) = \frac{1}{C_k k}\frac{d\varepsilon}{dt} + \frac{\varepsilon}{C_k}\frac{d(1/k)}{dt} = \frac{1}{C_k k}\frac{d\varepsilon}{dt} - \frac{\omega}{k}\frac{dk}{dt}$$

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- Hence, the commutation error in the ω equation is the commutation term in the k equation multiplied by $-\omega/k$ so that

$$\overline{\frac{\partial u_i \omega}{\partial x_i}} = \frac{\partial \bar{u}_i \omega}{\partial x_i} - \frac{\partial \Delta}{\partial x_i}\frac{\partial \bar{u}_i \omega}{\partial \Delta} = \frac{\partial \bar{u}_i \omega}{\partial x_i} + \frac{\omega}{k}\frac{\partial \Delta}{\partial x_i}\frac{\partial \bar{u}_i k}{\partial \Delta}$$

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- The present approach is similar to adding the commutation term in PANS [3]

$$
f_k \frac{Dk_{tot}}{Dt} = \frac{D(f_k k_{tot})}{Dt} - k_{tot}\frac{Df_k}{Dt} = \frac{Dk}{Dt} - k_{tot}\frac{Df_k}{Dt}
$$

$$
\frac{D}{Dt} = \frac{\partial}{\partial t} + \bar{u}_i \frac{\partial}{\partial x_i}, \quad k_{tot} = k + \frac{1}{2}\langle u_i' u_i' \rangle
$$

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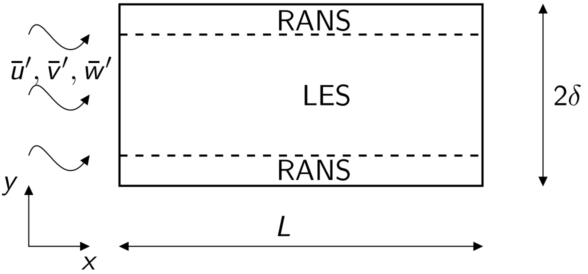
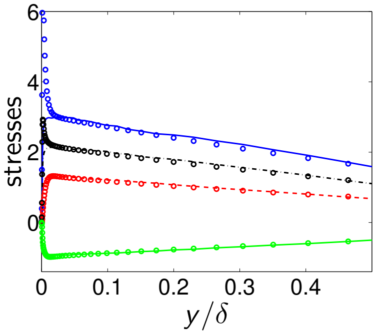
4. Finally, the synthetic fluctuations are scaled with $\left(|\overline{u'v'}|/|\overline{u'v'}|_{max}\right)^{1/2}_{RANS}$ which is taken from the RANS simulation.
5. Matlab codes can be downloaded [1] (Google "synthetic inlet fluctuations")

Channel flow

- Reynolds number is $Re_\tau = 8\,000$.
- A $256 \times 96 \times 32$ mesh is used
- $\Delta x = 0.1$, $\Delta z = 0.05$
- The mean U, k and ω taken from 1D RANS simulation using the PDH $k-\omega$ model
- The wall-parallel RANS-LES interface is prescribed at a fixed gridline at $y^+ \simeq 500$.



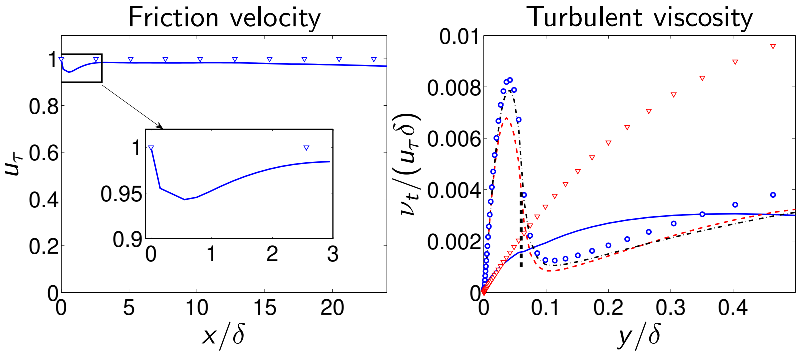
Inlet fluctuations



: $\langle u'u' \rangle^+$; : $\langle v'v' \rangle^+$; : $\langle w'w' \rangle^+$; : $\langle u'v' \rangle^+$.

Markers: EARSM.

Results



▽: $u_\tau = 1$ (target value)

━━: $x = 0.05\delta$; - - -: $x = 2.5\delta$; -·-: $x = 5.65\delta$; ▽: $\nu_t/(u_\tau\delta)/10$ at inlet (i.e. RANS).

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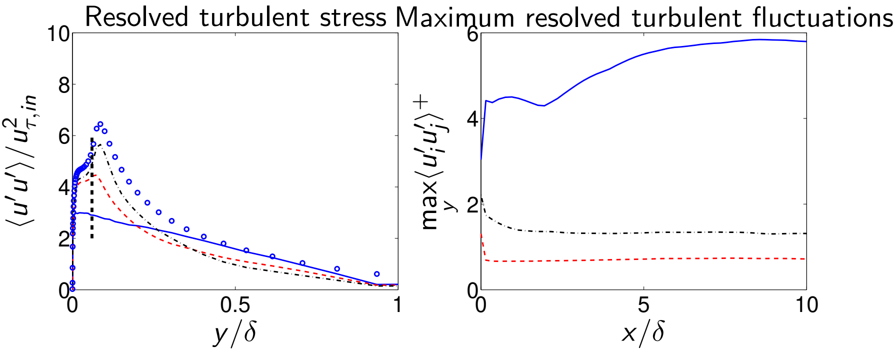
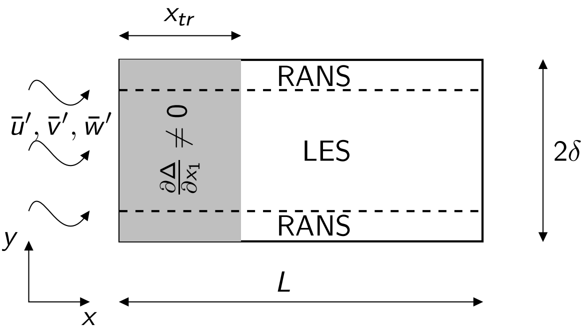


—: $x/\delta = 0.05$; – –: $x = 2.5\delta$; – · –: $x = 5.85\delta$; ○: fully developed channel flow with Zonal hybrid RANS-LES model.

—: $\langle u'u' \rangle^+$; – –: $\langle v'v' \rangle^+$; – · –: $\langle w'w' \rangle^+$.

Length of source region

- In how large a region, x_{tr}, should the commutation terms be added?



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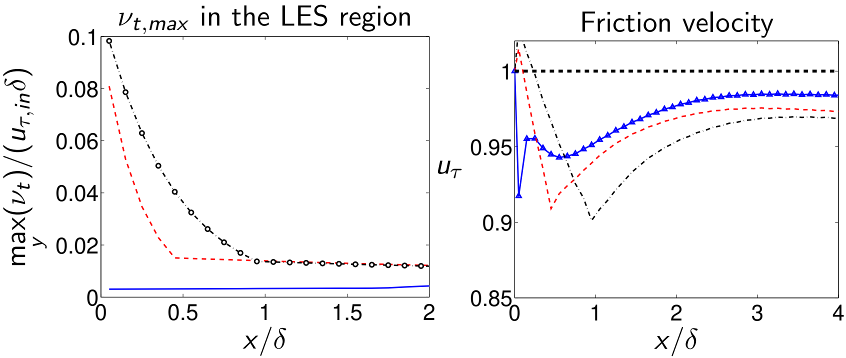
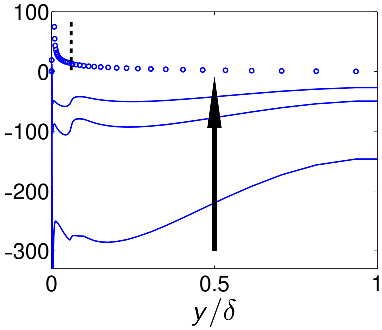


: $x_{tr}/\delta = 0.1$; : $x_{tr}/\delta = 0.5$; : $x_{tr}/\delta = 1$

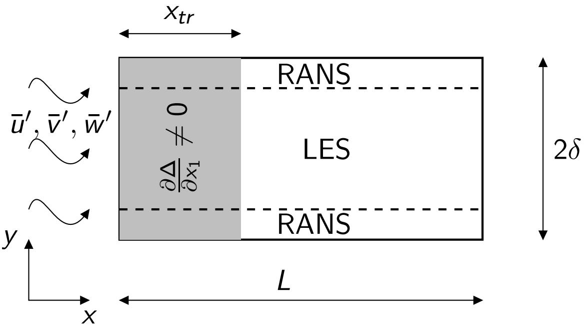
○: cell center

Source terms in k equation



$x/\delta = 0.05$. $\circ$: Production term, P^k, $x_{tr} = 0$.
—: commutation term. $(x_{tr}/\delta = 0.1, 0.5, 1)$
Arrow shows increasing x_{tr}

Commutation terms in the (U)RANS region?



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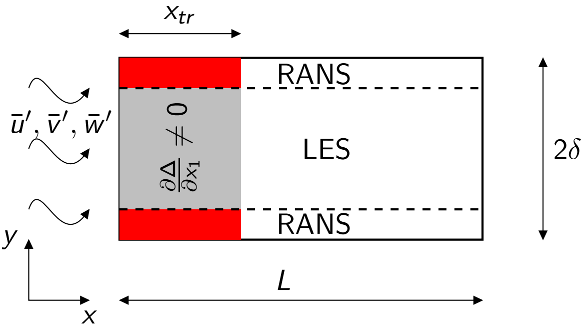

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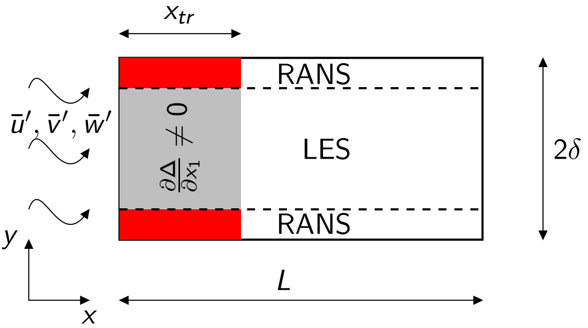
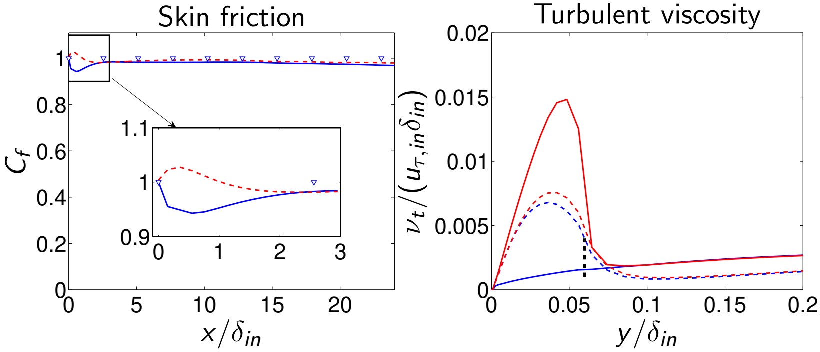


- Argument for using commutation terms in the (U)RANS region: $\nu_{t,URANS} \ll \nu_{t,RANS}$

Commutation term or not in (U)RANS region?

Blue lines: commutation terms in the (U)RANS region

Red lines: no commutation terms in the (U)RANS region



solid lines: $x/\delta_{in} = 0.05$

dashed lines: $x/\delta_{in} = 2.5$

Conclusions

- A novel method for prescribing inlet modelled turbulent quantities (k, ε, ω) has been presented
- It is based on the non-commutation between the divergence and the filter operators
- No tuning constants
- It is best to impose the commutation terms in one grid plane adjacent to the inlet

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