RANS/LES coupling with Synthetic-Eddy Method and controlled forcing: application to rotating channel flow

Benoît de Laage de Meux\(^1\)
Bruno Audebert\(^1\)
Rémi Manceau\(^2\)

\(^1\)MFEE/I85 Departement
EDF R&D, Chatou, France
benoit.de-laage-de-meux@edf.fr
bruno.audebert@edf.fr

\(^2\)Institute PPRIME, FTC Departement
CNRS–University of Poitiers–ENSMA, Poitiers, France
remi.manceau@univ-poitiers.fr

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Plan

1. Introduction
2. Turbulence models sensitive to rotation
3. RANS/LES coupling at inlet boundary using the Synthetic–Eddy Method
4. RANS/LES coupling on overlapping regions: a general controlled forcing
5. Conclusion
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Context, objectives

- Contribution to the development of Code_Saturne turbomachinery functionalities

⇒ What are the turbulence models adapted to rotating flows?

- Complex industrial applications in the turbomachinery field

Unsteady mixing between hot and cold water in some EDF pumps

- Complex physics: dynamic dominated by rotation, heat transfers
- Multiple time scales: rotor/stator interactions, turbulent time scales, heat transfers time scales
- Large computational domain

⇒ Which modelling strategy should be used?
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  ⇒ Which modelling strategy should be used?
RANS/LES zonal coupling should deal with the application mentioned above.

Previous work at EDF and UMIST:
- \textit{Code\_Saturne}/\textit{Code\_Saturne} coupling (available in the 2.0 version of the code)
- Synthetic inflow boundary conditions for LES (N. Jarrin thesis [4])

Each of the coupled RANS and LES model must be efficient for rotating flows.

\textbf{FIG. 2:} Zonal coupling concept and example of application

\textbf{Spanwise rotating channel test case}
- Stabilization (resp. destabilization) at suction (resp. pressure) side
- $2\Omega$ slope in the core of the channel
- Longitudinal roll cells at moderate rotation numbers
Strategy, test case

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1. **Introduction**

2. **Turbulence models sensitive to rotation**
   - RANS modelling
   - Large eddy simulation

3. **RANS/LES coupling at inlet boundary using the Synthetic–Eddy Method**

4. **RANS/LES coupling on overlapping regions: a general controlled forcing**

5. **Conclusion**
Statistical approach : RANS modelling (1/2)

Second moment closure (SMC):
- natural closure level to model the anisotropic effects of rotation

\[
\frac{dR_{ij}}{dt} = P_{ij} + \phi_{ij} + D_{ij} - \varepsilon_{ij}, \quad \phi_{ij} = f(b, S, \omega)
\]

\[
\frac{dR_{ij}}{dt} = P_{ij} + \phi_{ij} + D_{ij} - \varepsilon_{ij} + G_{ij}, \quad \phi_{ij} = f(b, S, W)
\]

- SSG model is better than LRR (suggested by equilibrium state analysis, confirmed by our computations, Fig. 3)
- Elliptic-blending Reynolds Stress Model [9] preserves the consistency of SSG model with linear stability analysis (Fig. 4)

**Fig. 3:** Mean velocity profiles. \(Re_\tau = 1500\), \(Ro_\tau = 5\). LRR model (solid lines) and SSG model (dashed line, profile shifted). Theoretical slope in the core of the channel are also shown.

**Fig. 4:** Blending function \(\alpha\) of the EBRSM. \(Re_b = 7000\), \(Ro_b = 0, 1/6, 0.5, 1.5\).
Statistical approach : RANS modelling (2/2)

Linear eddy-viscosity model (EVM) :
- no Coriolis effect in basic models
- some corrections for rotation and curvature (RC) have been proposed

RC corrections
- Spalart and Shur [12]
- Pettersson Reif et al [10]
- Cazalbou et al [1]

Basic models
- $k - \omega$ SST
- $\phi - f$ (Laurence et al [8])
- Lauder-Sharma

**Fig. 5:** Mean velocity (left), turbulent kinetic energy (center) and Reynolds shear stress (right) for increasing rotation rates (profiles are shifted).

$Re_b = 2500$, $Ro_b = 0, 1/6, 0.5, 1.5$.
- : DNS [7], -- : C-LS, --- : SS-SST, ---- : PR-$f$, --- : EBRSM.
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**Fig. 5:** Mean velocity (left), turbulent kinetic energy (center) and Reynolds shear stress (right) for increasing rotation rates (profiles are shifted). $Re_b = 2500$, $Ro_b = 0$, $1/6$, $0.5$, $1.5$.
- : DNS [7], – : C-LS, — : SS-SST, --- : PR-$\phi$-$f$, ---- : EBRSM.
Space-filtered approach: SGS modelling

Well resolved LES were conducted: $(\Delta_x^+, \Delta_y^+, \Delta_z^+) \sim (20, 1, 10)$ in the non-rotating case, same mesh for all rotation rates.

**Fig. 6:** Mean velocity (left) and resolved turbulent kinetic energy (right) in wall coordinates at pressure ($p$) (resp. suction ($s$)) side of the channel, for increasing rotation rates (profiles are shifted). $Re_b = 7000$, $Ro_b = 0, 1/6, 0.5, 1.5$.

Rotation acts mainly on the large scale (resolved) flow (see Jacquin et al [3] and Fig. 7) $\Rightarrow$ all models give satisfactory results.

Specific features

- **WALE model:** $\nu_{SGS} \sim \Omega^{4.8}$ $\Rightarrow$ inaccurate at high rotation rates
- **dynamic model (local)** accurate at moderate rotation rates
Coupling with the Synthetic–Eddy Method: formulation

Synthetic-Eddy Method (SEM) concept: fluctuations at a LES inflow boundary are generated by a set of eddies convected, by the bulk mean velocity, in a virtual box surrounding the inlet plane

\[
\widetilde{u}_i(x) = \langle \widetilde{u}_i(x) \rangle + \frac{1}{\sqrt{N}} \sum_{\lambda=1}^{N} \sum_{j=1}^{3} a_{ij}(x) \epsilon_{j}^{\lambda} f_{\sigma}(x)(x - x^{\lambda}),
\]

- \( \langle \widetilde{u}_i \rangle, (a_{ij}) \) : target first and second order moments
- \( \epsilon_{k}^{\lambda}, f_{\sigma}(x)(x - x^{\lambda}) \) : sign and magnitude of the fluctuations generated by eddy \( \lambda \), depending on:
  - its position \( x^{\lambda} \) (updated at each time step)
  - the characteristic turbulent length scale \( \sigma \)

Coupling:

- With an upstream EVM (Jarrin et al. [5]):
  \[
  \sigma = \max \left\{ \min \left\{ \frac{k^{3/2}}{\epsilon}, \kappa \delta \right\}, \Delta \right\}, \quad \Delta = \max\{\Delta_x, \Delta_y, \Delta_z\}, \quad \kappa = 0.41
  \]
- Generalization for SMC:
  \[
  \sigma_i = \max \left\{ \min \left\{ \frac{\left( \frac{3}{2} u'_i u'_i \right)^{3/2}}{\epsilon}, \kappa \delta \right\}, \Delta_i \right\}
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Coupling: evaluated from an upstream RANS computation

- With an upstream EVM (Jarrin et al [5]):
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- Generalization for SMC:
  \[ \sigma_i = \max \left\{ \min \left\{ \left( \frac{3}{2} u'_i u'_i \right)^{3/2} \right\}, \kappa \delta \right\}, \Delta_i \]
Coupling with the Synthetic–Eddy Method

An upstream periodic RANS computation coupled by SEM with a spatially developing LES

- RC sensitive models in the RANS region: SS-SST and EBRSM
- LES region: Smagorinsky model, \((\Delta_x^+, \Delta_y^+, \Delta_z^+) \approx (50, 2, 15)\) mesh (scaled on the friction velocity of the non-rotating case)

**Fig. 8:** Non rotating case. Friction coefficient (top) and normalized integral error (bottom) of resolved kinetic energy (solid lines) and shear stress (dashed lines).

**Fig. 9:** Rotating case: \(Ro_b = 1/6, 0.5\) (profiles are shifted). Mean velocity (top) and resolved kinetic energy (bottom). From left to right: \(x = 5, x = 10, x = 15, x = 30\).

Especially in the rotating case, anisotropic SEM takes value of the finer EBRSM predictions in the RANS region.
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4. **RANS/LES coupling on overlapping regions : a general controlled forcing**
   - Introduction
   - Straightforward approaches
   - The new approach
5. Conclusion
Goal, literature survey and formalism

Basic equations (LES domain) \( \frac{\partial \tilde{u}_i}{\partial t} + \cdots = \cdots + f \)

Volumic RANS/LES coupling (forcing) should help to:
- Allow a faster development of realistic turbulence
  - Inflow coupling: Spille-Kohoff and Kaltenback [13]. A controller of the error between resolved and target shear stress is used to adapt the wall normal fluctuations. Successfully applied by Keating et al [6] for hybrid RANS/LES.
  - Tangential coupling: Davidson and Billson [2]. Synthetized fluctuations are super-imposed in the momentum equations.
- Drive a (eventually low resolved) LES toward target moments (given by a background RANS computation)
  - Outflow coupling: Schlüter et al [11]. A relaxation term between RANS and LES variables is introduced.

⇒ Large scope of applications, various formulations

Present proposal focuses on the influence of the forcing on resolved moments:

\[
\begin{align*}
    f = \tilde{f} + f' & \Rightarrow \\
    \frac{\partial \tilde{u}_i}{\partial t} + \cdots = \cdots + \tilde{f} & + \cdots + \left( \frac{\partial \tilde{u}_i \tilde{u}_j}{\partial t} + \cdots + \tilde{u}_i' \tilde{f}'_j + \tilde{u}_j' \tilde{f}_i' \right) \\
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⇒ Large scope of applications, various formulations

General sketch of an embedded LES in a surrounding RANS computation
Straightforward approaches

The relaxation approach is quite intuitive (see Schlüter et al [11]).

- **Mean velocity forcing**: \( f_i = \bar{f}_i = \frac{1}{\tau} (\bar{u}_i^{\text{RANS}} - \bar{u}_i) \), with \( \tau \) a relaxation time

  Here, \( \bar{u}_i = \langle \hat{u}_i \rangle \Delta_t \), with \( \langle \cdot \rangle \Delta_t \) an exponential time filtering of size \( \Delta_t = 10 \frac{k}{\varepsilon} \)

  ![Fig. 10: SEM with mean velocity forcing: friction coefficient. \( Re_b = 7000 \), \( Ro_b = 0 \).](image)

  \( f'_i = 0 \Rightarrow P_{ij}^f = 0 \)

  - No significant effect with this forcing

- **Instantaneous velocity forcing**: \( f_i = \bar{f}_i = \frac{1}{\tau} (\bar{u}_i^{\text{RANS}} - \hat{u}_i) \)

  ![Fig. 11: SEM with instantaneous velocity forcing: friction coefficient (left) and example of velocity signal in the forcing zone (right).](image)

  \( P_{ij}^f = -\frac{2}{\tau} \hat{u}_i \hat{u}_j' \)

  - Fluctuations are damped
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Fig. 10: SEM with mean velocity forcing: friction coefficient. \( Re_b = 7000 \), \( Ro_b = 0 \).

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General controlled forcing: formulation

- General fluctuating force written as: \( f_i = A_{ik} \tilde{u}_k + B_i \)
  - \( A_{ij} \) a symmetric tensor (6 components), \( B_i \) a vector (3 components)

\[
\begin{align*}
\vec{f}_i & = A_{ik} \bar{u}_k + B_i \\
P^f_{ij} & = A_{ik} \bar{u}_j \bar{u}_k + A_{jk} \bar{u}_i \bar{u}_k
\end{align*}
\]

- Idea: model \( P^f_{ij} \) (6 equations) and \( \vec{f}_i \) (3 equations) to compute \( A_{ij} \) and \( B_i \).
- Current approach: relaxation

\[
\begin{align*}
A_{ik} \tilde{u}_j \tilde{u}_k' + A_{jk} \tilde{u}_i \tilde{u}_k' & = \frac{1}{\tau} \left( \bar{u}_i' \bar{u}_j'_{\text{RANS}} - \bar{u}_i' \bar{u}_j' \right) \\
A_{ik} \bar{u}_k + B_i & = \frac{1}{\tau} \left( \bar{u}_i'_{\text{RANS}} - \bar{u}_i \right)
\end{align*}
\]  \hspace{1cm} (1)

- Ensemble average is approximated by an exponential time filtering of size \( \hat{\Delta}_t = 10^k \frac{\epsilon}{\bar{u}} \)
- (1) solved directly with the LU method at each cell of the overlapping region.
  Then (2) is diagonal.
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A_{ik} \bar{u}_j \bar{u}_k' + A_{jk} \bar{u}_i \bar{u}_k' &= \frac{1}{\tau} (\bar{u}_i' \bar{u}'^{\text{RANS}} - \bar{u}_i' \bar{u}_j') \\
A_{ik} \bar{u}_k + B_i &= \frac{1}{\tau} (\bar{u}_i^{\text{RANS}} - \bar{u}_i) 
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Synthetic turbulence + controlled forcing: some results

An upstream periodic RANS computation (EBRSM) coupled by SEM and controlled forcing with a spatially developing LES (Smagorinsky)

\[ \tau = \beta \frac{U_b}{L} \] with \( U_b \) the bulk velocity, \( L \) the overlapping length and \( \beta \leq 1 \). Here we chose \( L = 5 \) and \( \beta = 0.5 - 1 \).

**Fig. 12:** Non rotating case. Friction coefficient (top) and normalized integral error (bottom) of resolved kinetic energy (solid lines) and shear stress (dashed lines).

**Fig. 13:** Rotating case: \( Ro_b = 1/6, 0.5 \) (profiles are shifted). Mean velocity (top) and resolved kinetic energy (bottom). From left to right: \( x = 5, x = 10, x = 15, x = 30 \).

The controlled forcing allows a better development of the turbulence in the overlapping region, but not significantly out of it.
Controlled forcing without synthetic turbulence

- Sufficient to develop fluctuations
- Useful case for a closer understanding of the forcing effect: work in progress...

Present computation: EBRSM velocity profile at inlet + controlled forcing with $\tau = 1$ all over the LES region

**Fig. 14:** Mean velocity (left) and resolved kinetic energy (right). $Re_b = 7000$, $Ro_b = 0$.

$\cdots : x = 5$, $\cdots : x = 10$, $\cdots : x = 15$, $\cdots : x = 30$.

**Fig. 15:** Isocontours of longitudinal fluctuating velocity. $y = 0.99$ (top), $y = 0.8$ (middle), $y = 0$ (bottom)

RANS moments are very well reproduced but, in the core of the channel and near the inflow:

- coherent structures unrealistic
- parasitical frequency on the amplitude of fluctuations

Instantaneous longitudinal velocity signal ($\cdots$) and time-filtered longitudinal second moment ($\cdots$)
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Conclusion, future works

Conclusion:

- Systematic confrontation of numerous turbulence models on the rotating channel test case:
  - RANS models: we retain EBRSM for SMC and Spalart-Shur correction + \( k-\omega \) SST for EVM
  - well resolved LES: slight superiority of dynamic Smagorinsky model
- RANS/LES coupling with SEM:
  - efficient for rotating flows
  - importance of SMC (EBRSM) in the upstream RANS region
- Volumic RANS/LES coupling: a new controlled forcing is proposed
  - successfully applied near the LES inflow, in association with SEM at boundary

Future works:

- Controlled forcing:
  - isotropic turbulence test case, tangential coupling (?), ...
  - possible evolution of the formulation

- Generalisation of the RANS/LES coupling (SEM and forcing) to heat fluctuations
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Thank you for your attention!
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