APPLICATION OF ZONAL HYBRID URANS/LES MODELING TO INTERNAL COMBUSTION ENGINE FLOWS

V. K. Krastev¹, A. D’Adamo², S. Breda³, S. Fontanesi²

¹ Department of Economics, Engineering, Society and Business Organization, University of Tuscia, 01100 Viterbo, Italy

² DIEF - "Enzo Ferrari" Engineering Department, University of Modena and Reggio Emilia, 41125 Modena, Italy

³ R&D CFD SRL - Via Pietro Vivarelli 2, 41125 Modena, Italy
Outline

• Background
  o URANS/LES hybrids in ICE modeling
  o Motivations

• Zonal modeling formulation & calibration

• Applications
  o Static valve intake flow
  o TCC-III Engine multi-cycle analysis

• Conclusions
Outline

- Background
  - URANS/LES hybrids in ICE modeling
  - Motivations

- Zonal modeling formulation & calibration

- Applications
  - Static valve intake flow
  - TCC-III Engine multi-cycle analysis

- Conclusions
Outline

• Background
  o URANS/LES hybrids in ICE modeling
  o Motivations

• Zonal modeling formulation & calibration

• Applications
  o Static valve intake flow
  o TCC-III Engine multi-cycle analysis

• Conclusions
Outline

• Background
  o URANS/LES hybrids in ICE modeling
  o Motivations

• Zonal modeling formulation & calibration

• Applications
  o Static valve intake flow
  o TCC-III Engine multi-cycle analysis

• Conclusions
Background

URANS/LES hybrids in the ICE modeling community

- LES methods for ICE modeling are being developed for 25 years, **but** ...
- ... in recent years the interest for URANS/LES hybrids is apparently **growing**
- Potential gains in computational **robustness and efficiency**, keeping **scale-resolving capabilities** where needed
- Several seamless (SAS, DES, DLRM) and zonal (ZDES) alternatives proposed

*Cumulative graph of the published journal papers with relevant hybrid URANS/LES applications in the ICE field (source*: [www.scopus.com](http://www.scopus.com))

*The collected data might not be fully exhaustive*
Background

URANS/LES hybrids in the ICE modeling community

- LES methods for ICE modeling are being developed for 25 years, but ...

- …in recent years the interest for URANS/LES hybrids is apparently growing

- Potential gains in computational robustness and efficiency, keeping scale-resolving capabilities where needed

- Several seamless (SAS, DES, DLRM) and zonal (ZDES) alternatives proposed

Cumulative graph of the published journal papers with relevant hybrid URANS/LES applications in the ICE field (source*: www.scopus.com)

*The collected data might not be fully exhaustive
Background

URANS/LES hybrids in the ICE modeling community

- LES methods for ICE modeling are being developed for 25 years, **but** …
- … in recent years the interest for URANS/LES hybrids is apparently **growing**
- Potential gains in computational **robustness and efficiency**, keeping **scale-resolving capabilities** where needed
- Several seamless (SAS, DES, DLRM) and zonal (ZDES) alternatives proposed

**Cumulative graph of the published journal papers with relevant hybrid URANS/LES applications in the ICE field** (source*: [www.scopus.com](http://www.scopus.com))

*The collected data might not be fully exhaustive*
Meanwhile, in the aerospace/turbomachinery engineering fields...

Complete aircraft at scale 1:1 in true flight conditions (Ma=0.8, Re ~ 5\cdot10^7, ~ 2\cdot10^8 grid points)*


- DES and Zonal-DES modeling have proven to be highly efficient in complex aerospace applications
- The flexibility of hybrid modeling allows the accurate resolution of different types of internal and external, flows within the same computational domain
- Care is needed for the optimal domain decomposition and numerics choice
Background

Why (Z)DES for ICE?

- Single, URANS-based turbulence modeling framework
- Activation of LES only where actually needed
- Less troublesome BCs
- Reported to be competitive with LES on sub-optimal grids, especially for wall-impinging flows

*See e.g. K. Keskinen et al. *International Journal of Heat and Fluid Flow* 65 (2017) 141−158*
More specifically:

- Assess if a (relatively) basic ZDES model is capable of handling complex multi-cycle engine simulations with a reasonable level of accuracy
  - Comparable with experimental data sets
  - Comparable with modern LES approaches on engineering-grade meshes
From two-equation URANS to (Z)DES

**Basis:**

- General URANS two-equation form:

\[
\frac{\partial k}{\partial t} + C_k = P_k - S_k + D_k \\
\frac{\partial \psi}{\partial t} + C_\psi = P_\psi - S_\psi + D_\psi \\
\mu_t = f(k, \psi)
\]

- Strelets et al. (2001) showed that URANS can be turned into DES by modifying \(S_k\) only

**TKE sink term modification (1)**
From two-equation URANS to (Z)DES

**Basis:**

1. General URANS two-equation form:
   \[
   \frac{\partial k}{\partial t} + C_k = P_k - S_k + D_k \\
   \frac{\partial \psi}{\partial t} + C\psi = P\psi - S\psi + D\psi \\
   \mu_t = f(k, \psi)
   \]

2. Strelets et al. (2001) showed that URANS can be turned into DES by modifying \( S_k \) only

**TKE sink term modification (1)**

\[
S_{k,\text{RANS}} = \frac{k^{3/2}}{l_{\text{RANS}}} \quad ; \quad l_{\text{RANS}} = f(k, \psi)
\]

\[
S_{k,\text{DES}} = \frac{k^{3/2}}{l_{\text{DES}}} \quad ; \quad l_{\text{DES}} = \min(l_{\text{RANS}}, C_{\text{DES}}\Delta)
\]

\[
\Delta = f(\text{grid}) \\
C_{\text{DES}} = O(1)
\]
From two-equation URANS to (Z)DES

**Basis:**

- General URANS two-equation form:
  \[
  \frac{\partial k}{\partial t} + C_k = P_k - S_k + D_k \\
  \frac{\partial \psi}{\partial t} + C_\psi = P_\psi - S_\psi + D_\psi \\
  \mu_t = f(k, \psi)
  \]

- Strelets et al. (2001) showed that URANS can be turned into DES by modifying \( S_k \) only

**TKE sink term modification (1)**

\[
S_{k,\text{RANS}} = \frac{k^{3/2}}{l_{\text{RANS}}} \quad ; \quad l_{\text{RANS}} = f(k, \psi)
\]

\[
S_{k,\text{DES}} = \frac{k^{3/2}}{l_{\text{DES}}} \quad ; \quad l_{\text{DES}} = \min(l_{\text{RANS}}, C_{\text{DES}} \Delta)
\]

\[
S_{k,\text{DES}} = F_{\text{DES}} S_{k,\text{RANS}}
\]

\[
F_{\text{DES}} = \max \left[ l_{\text{RANS}} / (C_{\text{DES}} \Delta), 1 \right]
\]

*Final form*
From two-equation URANS to (Z)DES

Seamless DES:
- URANS-to-LES managed entirely by the model (user decisional load kept to a minimum), but…
- …the triggering mechanism is not always efficient

Zonal DES:
- URANS and LES (or DES) regions explicitly marked by the user
- Better control of the solution behavior (at the expense of nontrivial a-priori decisions)
- Good candidate for complete ICE simulation

TKE sink term modification (2)

\[
S_{k,DES}^* = F_{DES}^* S_{k,RANS}
\]

\[
F_{DES}^* = C_{z1} F_{DES} + (1 - C_{z1}) F_{ZDES}
\]

\[
F_{ZDES} = C_{z2} + (1 - C_{z2}) \left( \frac{l_{RANS}}{C_{DES}\Delta} \right)
\]
From two-equation URANS to (Z)DES

**Seamless DES:**

- URANS-to-LES managed entirely by the model (user decisional load kept to a minimum), but...
- ...the triggering mechanism is not always efficient

**Zonal DES:**

- URANS and LES (or DES) regions explicitly marked by the user
- Better control of the solution behavior (at the expense of nontrivial a-priori decisions)
- Good candidate for complete ICE simulation

**TKE sink term modification (2)**

\[
S_{k,DES}^* = F_{DES}^* S_{k,RANS}
\]

\[
F_{DES}^* = C_{z1} F_{DES} + (1 - C_{z1}) F_{ZDES}
\]

\[
F_{ZDES} = C_{z2} + (1 - C_{z2}) \left( \frac{l_{RANS}}{C_{DES} \Delta} \right)
\]

<table>
<thead>
<tr>
<th>( C_{z1} )</th>
<th>( C_{z2} )</th>
<th>Simulation type</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>URANS</td>
<td>I</td>
</tr>
<tr>
<td>1</td>
<td>1/0</td>
<td>DES</td>
<td>II</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>LES</td>
<td>III</td>
</tr>
</tbody>
</table>
Implementation overview

**Which turbulence model?**

- RNG k-\(\varepsilon\) model
  - Improved, shear-dependent \(\varepsilon\)-equation
  - Widely adopted in the ICE community

**Which CFD code?**

- STAR-CD v4.22c (Siemens PLM)
  - Unstructured FVM code
  - Second-order accurate in space and time
  - ZDES formulation implemented through user-supplied Fortran subroutines

**Methodology implementation/calibration:**

- The \(C_{\text{DES}}\) value must ensure a consistent turbulent energy decay in mode III (pure LES)

- The optimal value depends on:
  - the specific underlying turbulence model (k-\(\varepsilon\), k-\(\omega\),…)
  - the accuracy/behavior of the discretization schemes

- Calibration tests needed
C_{DES} calibration: turbulence box

- Standard test for DNS and SGS models
- Cubic domain with cyclic BCs in each direction, $N^3$ perfectly cubic cells ($N=64$)
- Flow field initialized with an incompressible divergence-free turbulent spectrum
  - Turbulence is left to spontaneously decay driven by mode III of ZDES
- $C_{DES}$ is varied in the 0.4-0.61 range
- MARS scheme for momentum convection (BF = 0.5 and BF = 1)
- Comparisons with the Comte-Bellot and Corrsin § database (energy spectra)

$^{+}C_{DES} = 0.61$ is the first “standard” value reported in the literature for k-ε based DES models

The BF effect is dominant

- BF = 1 assumed as default for the LES mode (mode III)
- $C_{DES} = 0.61$ assumed as standard
Case overview

Preliminary remarks:

- Intake port geometry with an axis-centered fixed poppet valve, $Re_b \approx 3 \times 10^4$

- LDA (velocity) and axial pressure measurements available

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve Stem Diameter ($D_v$)</td>
<td>16 mm</td>
</tr>
<tr>
<td>Intake Duct Diameter ($D_i$)</td>
<td>34 mm</td>
</tr>
<tr>
<td>Cylinder Diameter ($D_c$)</td>
<td>120 mm</td>
</tr>
<tr>
<td>Valve Head Diameter ($D_v$)</td>
<td>40 mm</td>
</tr>
<tr>
<td>Intake Duct Length ($L_i$)</td>
<td>140 mm</td>
</tr>
<tr>
<td>Cylinder Length ($L_c$)</td>
<td>300 mm</td>
</tr>
<tr>
<td>Valve Lift ($L_L$)</td>
<td>10 mm</td>
</tr>
<tr>
<td>Inlet Bulk Velocity ($U_b$)</td>
<td>60 m/s</td>
</tr>
<tr>
<td>Fluid</td>
<td>air at NIST standard conditions</td>
</tr>
<tr>
<td>Inlet Bulk Reynolds Number ($Re_b$)</td>
<td>$\sim 3 \times 10^4$</td>
</tr>
</tbody>
</table>
Case overview

**Preliminary remarks:**

- Intake port geometry with an axis-centered fixed poppet valve, $\text{Re}_b \approx 3 \times 10^4$
- LDA (velocity) and axial pressure measurements available
- **Mode I** numerics: MARS 0.5 for momentum and scalars
- **Mode II/III** numerics: MARS 1 for momentum, MARS 0.5 for scalars
- Standard inflow/outflow incompressible BCs, WFs at the walls
- Comparisons with experiments and OpenFOAM results (same turbulence model and grid, similar numerics)
Applications – Static valve

Results (x = 20 mm)

- Significant improvements compared to steady RANS profiles (code-by-code differences due to numerics)
- Z1 and Z2 time-averaged profiles very close (Mode II is likely to trigger LES in most of the domain)
Results (axial pressure development)
Results (axial pressure development)

- Even more pronounced improvements compared to RANS (same code-by-code differences)
- Z1 and Z2 time-averaged profiles very close (Mode II is likely to trigger LES in most of the domain)
Case overview

**Preliminary remarks (1):**

- Selected for the **ease of reproduction** and large experimental PIV data set
- **1300 RPM and 40 kPa** intake manifold pressure
- Availability of LES data sets from UniMoRe

---

<table>
<thead>
<tr>
<th>Engine Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
</tr>
<tr>
<td>Stroke</td>
</tr>
<tr>
<td>Connecting rod length</td>
</tr>
<tr>
<td>Geometrical compression ratio</td>
</tr>
<tr>
<td>Operation</td>
</tr>
<tr>
<td>N. of valves</td>
</tr>
<tr>
<td>Combustion chamber type</td>
</tr>
<tr>
<td>RPM</td>
</tr>
<tr>
<td>Intake manifold pressure</td>
</tr>
</tbody>
</table>
Case overview

**Preliminary remarks (2):**

- Full domain splitted in 5 zones (cylinder, intake/exhaust ports, plenums)
- Only the cylinder zone treated in scale-resolving mode (Mode II or Mode III)
- Max 2M cells at BDC, ~ 0.75 mm base cell dimension in the cylinder

Mode II = TCC-Z1
Mode III = TCC-Z2
Case overview

\[ u_i = \frac{1}{n} \sum_{j=1}^{n} u_{i,j} \]

\[ u_{i,rms} = \sqrt{\frac{1}{(n-1)} \sum_{j=1}^{n} (u_{i,j} - \langle u_i \rangle)^2} \]

\[ i = \text{PIV grid point} \]
\[ j = \text{cycle number} \]
\[ n = 50 \]

**Preliminary remarks (3):**

- Postprocessing initially focused on the **vertical planes**

- **S_2013_10_24_01** and **S_2014_02_05_02** reference data sets (same windows/resolution in the simulations)

- Previous **LES DSM** results (on the same CFD grid) added for comparison
Results (Y = 0): 475 CA
Results ($Y = 0$): 475 CA

- Good **average jet shape** prediction by TCC-Z1 (added modeled viscosisty?)
- Underestimation of RMS fluctuations close to the piston head
Results (Y = 0): 540 CA
Results (Y = 0): 540 CA

- DSM closer to experiments
- TCC-Z1 slightly more consistent with DSM and experiments
Results (Y = 0): 630 CA
Results (Y = 0): 630 CA

- DSM still in good agreement with the experiments
- Anomalous shift of the RMS peak values
Results ($X = 0$): 475 CA

- **Good overall consistency** for all numerical predictions
- Small differences persist between TCC-Z1 and TCC-Z2
Results (X = 0): 540 CA
Results (X = 0): 540 CA

- Much better **main vortex average shape** description for TCC-Z1 and TCC-Z2
- DSM seems to overestimate RMS fluctuations
Results (X = 0): 630 CA
Results (X = 0): 630 CA

- Vortex compression **better described by DSM**
- TCC-Z1 (still) **slightly more consistent** than TCC-Z2 (average flow)
Final remarks

- Is the evaluated ZDES formulation *reasonably adequate* for engine multi-cycle simulation?
Final remarks

- Is the evaluated ZDES formulation reasonably adequate for engine multi-cycle simulation?

Yes, but...
What’s next?

- More TCC-III results (in progress):
  - complete the analyses on the vertical planes (LES quality indicators, LES or DES for the cylinder);
  - more planes;
  - different zonal setups.

- Modeling aspects (LES mode, wall modeling)

- Different engines (pentroof, 4 valves, GDI?)

- Combustion?
Acknowledgments

✓ **GM** (through the GM University of Michigan Automotive Cooperative Research Laboratory, Engine Systems Division).

✓ **Siemens PLM Software Inc.**

✓ **TCC-III database**

✓ **STAR-CD software licensing** (through UniMoRe HPC resources)
Thank you!