Effects of meshing strategies on in-cylinder flows

Internal Combustion Engine Research Group:

S. Fontanesi, F. Rulli, F. Testa
Overset Mesh for the Simulation of Internal Combustion Engine Flows

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➢ Why Back Again on Overset Mesh

➢ Mass conservation
  • Early 2016 results
  • Test Case and recent results

➢ Overset application on TCC engine
  • Why TCC engine
  • Domain Creation & Assembly, Numerical Setup

➢ Results
  • LES-Experimental comparison (STAR-CCM+ and STAR-CD)

➢ Conclusion & Future Developments
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WHY BACK AGAIN ON OVERSET

Standard Workflow: STAR-CD/es-ice and/or STAR-ICE (layer addition / removal, mesh morphing / remapping)...

...but there are situations where non of the above techniques will work unless a painful procedure is set up!

That’s why we started a detailed Overset Mesh exploration in order to assess its potential as a technology for ICE simulations.

Overset Method:

- Helps execute analyses which require complex motion or contact of objects, which can hardly be simulated with a single mesh
- Allows the use of any combination of mesh topologies
- Allows single part replacing
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S. Fontanesi, F. Testa

Relevant mass conservation errors
Test case to evaluate and reduce mass conservation error

**SIMPLIFIED CYLINDER**
- Bore: 90 mm
- Stroke: 70 mm
- Height of combustion chamber at TDC: 4 mm
- Height of "piston" region: 4 mm
- Angular velocity of imaginary engine’s crankshaft: 100 RPM
- Volume at BDC: 470.7677 cm$^3$
- Volume at TDC: 25.4460 cm$^3$
- Compression Ratio $R_C$: 18.5

**CHALLENGING CONDITIONS FOR OVERSET MESH TECHNIQUE**
- Closed volume
- No valves or ducts
- Flat head and flat piston
**BASE CASE**

- Time-step: $0.0005$ s (2nd order)
- Hexahedral cells (TRIM MESH)
- Prism layer (not on horiz surfaces)
- Cells base size: $1$ mm

Mass conservation error with default settings is unacceptable.

Multiple tests to search for optimal settings and to validate software options.

**TEMPORAL DISCRETIZATION SCHEME:** 1st and 2nd order

**VARIOUS TIME- STEPS:** from $0.001$ to $0.000025$ sec.

**HOLE CUTTING TECHNIQUES:**
- LAYERED HOLE CUTTING
- ALTERNATE HOLE CUTTING

**MESH SET-UP:**
- TRIMMED MESH
- POLYHEDRAL MESH
- Lowered piston region
- DIFFERENT MESH SIZES in overlapping area

**ANALYTICAL MASS**
Simplified cylinder test of interpolation options using different time-steps.

**INTERPOLATION OPTIONS:**
- DISTANCE WEIGHTED
- LINEAR
- LEAST SQUARE

**TIME-STEMS:**
- 0.0005 s
- 0.00025 s
- 0.0001 s

**MESH TYPE:**
- TRIMMED MESH
- POLYHEDRAL MESH

**MASS CONSERVATION: TEST CASE**

MAX MASS ERROR = +1.5%

MAX MASS ERROR = -2.7%
Simplified cylinder test of time-steps values used in standard ICE simulations (with alternate hole cutting and linear interpolation option).

**TIME-STEMPS:**
- 0.0005 s
- 0.00025 s
- 0.0001 s
- 0.00005 s
- 0.000025 s

**MESH TYPE:**
- TRIMMED MESH
- POLYHEDRAL MESH

**MASS CONSERVATION: TEST CASE**

**MAX MASS ERROR = +0.8%**

**TIME**

- 0.00025 s
- 0.0005 s
- 0.001 s
- 0.00025 s
- 0.0005 s

**REFERENCE:** t-step = 0.0005 s, "Layered Hole Cutting"

**MAX MASS ERROR = -1.2%**

**REFERENCE:** t-step = 0.0005 s, "Layered Hole Cutting"
Optimal settings for simplified cylinder test case:

• 2nd order time discretization
• Linear/least square interpolation
• Alternate hole cutting
• Overlap volume calculation
• STAR-CCM+ vers. 11.04 or newer

More than 300 different configurations were evaluated during this analysis.
TOPICS

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The TCC-III is a spark ignition 4-stroke 2-valve engine with a flat head and piston. It is equipped with a full quartz liner for maximum optical access that allows high-speed flow measurements with Particle Image Velocimetry (PIV)

<table>
<thead>
<tr>
<th>TCC-III Engine Geometry</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore, cm</td>
<td>9.20</td>
<td>Conrod length, cm</td>
</tr>
<tr>
<td>Stroke, cm</td>
<td>8.60</td>
<td>piston-pin offset, cm</td>
</tr>
<tr>
<td>Clearance @ TDC</td>
<td>0.95</td>
<td>conn rod offset</td>
</tr>
<tr>
<td>Comb Chamber, cc</td>
<td>63.15</td>
<td>EVC, aTDCexh</td>
</tr>
<tr>
<td>Top Land Crevice, cc</td>
<td>0.37</td>
<td>IPL, aTDCexh</td>
</tr>
<tr>
<td>SpkPlug crevice, cc</td>
<td>0.02</td>
<td>IVC, aTDCexh</td>
</tr>
<tr>
<td>TDC Vol., cc</td>
<td>63.54</td>
<td>EVO, aTDCexh</td>
</tr>
<tr>
<td>Swept Vol, cc</td>
<td>571.7</td>
<td>EPL, aTDCexh</td>
</tr>
<tr>
<td>Geometric CR</td>
<td>10.00</td>
<td>IVO, aTDCexh</td>
</tr>
<tr>
<td>Effective (IVC) CR</td>
<td>8.00</td>
<td>Valve seat angles, deg</td>
</tr>
<tr>
<td>Steady-Flow Swirl Ratio</td>
<td>0.4</td>
<td>Delco Spk Plg</td>
</tr>
</tbody>
</table>
Vast scientific literature available on TCC engine

Strong background @ UniMORE with previous research on TCC engine:

- Cooperation with PSU, UMICH on motored engine conditions
  - Effects of sgs models on flow CCV\cite{1}, \cite{2}
- Cooperation with PSU, UMICH on firing engine conditions
  - Comparison between different ignition/flame propagation models\cite{3}
- Cooperation with SNU on motored engine conditions
  - Effects of grid size, numerics and sgs on flow CCV\cite{4}, \cite{5}
- Upcoming Cooperation with PSU, UMICH, SNU, ETH (others?) on firing engine conditions
  - Comparison between different ignition/flame propagation models at challenging engine conditions

\cite{1} “An Integrated Experimental and Simulation Study of Cycle-to-Cycle Variations in a Homogeneous-Charge Spark-Ignition Engine”, P. Schiffmann\textsuperscript{1}, S. Paltrinieri\textsuperscript{2}, Y. Shekhawat\textsuperscript{3}, D.L. Reuss\textsuperscript{3}, V. Sick\textsuperscript{3}, S. Fontanesi\textsuperscript{2}, D.C. Haworth\textsuperscript{3}; (1 University of Michigan, USA; 2 University of Modena and Reggio Emilia, Italy; 3 Pennsylvania State University, USA), International Multidimensional Engine Modeling User’s Group Meeting, 2014

\cite{2} “An experimental and simulation study of turbulent flow in a homogeneous-charge spark-ignition engine”, Y Shekhawat\textsuperscript{1}, S. Paltrinieri\textsuperscript{1}, P. Schiffmann\textsuperscript{3}, D.C. Haworth\textsuperscript{3}, S. Fontanesi\textsuperscript{2}, V. Sick\textsuperscript{3}, D.L. Reuss\textsuperscript{3}, (1 Pennsylvania State University, USA; 2 University of Modena and Reggio Emilia, Italy; 3 University of Michigan, USA), LES4ICE 2014

\cite{3} “An experimental and simulation study of early flame development in a homogeneous-charge SI engine”, Y. Shekhawat, D.C. Haworth (Pennsylvania State University, USA), A. d’Adamo, S. Fontanesi (University of Modena and Reggio Emilia, Italy), P. Schiffmann, D.L. Reuss, V. Sick (University of Michigan, USA)

\cite{4} “Study of LES Quality Criteria in a Motored Internal Combustion Engine”, SAE Technical Paper 2017-01-0549, I. Ko\textsuperscript{1}, A. D’Adamo\textsuperscript{2}, S. Fontanesi\textsuperscript{2}, K. Min\textsuperscript{1}, (1 Seoul National University, South Korea; 2 University of Modena and Reggio Emilia, Italy)

\cite{5} “Investigation of sub-grid model and grid density effects on the accuracy of in-cylinder LES of the TCC engine under motored conditions”, I. Ko\textsuperscript{1}, A. D’Adamo\textsuperscript{2}, F. Berni\textsuperscript{2}, S. Fontanesi\textsuperscript{2}, K. Min\textsuperscript{1}, (1 Seoul National University, South Korea; 2 University of Modena and Reggio Emilia, Italy)
PRELIMINARY RANS INVESTIGATION

- TRIM 1.0 mm
- POLY 1.0 mm
- TRIM 0.6 mm
- POLY 0.7 mm

LES/VLES PRELIMINARY ANALYSIS

Trim mesh Base Size 1.5 mm ≈ 1.5 million cells
RANS Application on mesh with different base size and topology

Experimental Results

PIV  |  POLY 0.7  |  TRIM 0.6  |  POLY 1.0  |  TRIM 1.0

RANS Simulations

- TRIM 1.0 mm
- POLY 1.0 mm
- TRIM 0.6 mm
- POLY 0.7 mm

Velocity Field at 470 CA On Y=0 plane

Vel. Mag. (m/s)

- 60.0
- 48.0
- 36.0
- 24.0
- 12.0
- 0.0
DOMAIN CREATION & ASSEMBLY, NUMERICAL SETUP

STAR-CD 422

- 42 cycles

PHYSICAL MODELS:
- Large Eddy Simulation
- Time: PISO (2\textsuperscript{nd} order)
- Dynamic Smagorinsky
- MARS (2\textsuperscript{nd} order) blending factor 1
- Temperature model (2\textsuperscript{nd} order)
- Equation of State: Ideal Gas
- Molecular Viscosity: polynomial
- Specific Heat: polynomial

Total Cells in cylinder at BDC: $1.15E06$

STAR-CCM+ 11.06

- 20 cycles

PHYSICAL MODELS:
- Large Eddy Simulation
- Time: Implicit Unsteady (2\textsuperscript{nd} order)
- Dynamic Smagorinsky
- MUSCLE 3\textsuperscript{rd} order/CD blending factor 1
- Segregated Fluid Temperature (2\textsuperscript{nd} order)
- Equation of State: Ideal Gas
- Dynamic Viscosity: Sutherland’s Law
- Specific Heat: polynomial in T

Total Cells in cylinder at BDC: $6E05$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>TCC-III engine</td>
</tr>
<tr>
<td>Displacement Volume</td>
<td>570 cc</td>
</tr>
<tr>
<td>Bore</td>
<td>92 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>86 mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>10.0</td>
</tr>
<tr>
<td>Engine Speed</td>
<td>1300 RPM</td>
</tr>
<tr>
<td>Intake Pressure</td>
<td>0.4 bar</td>
</tr>
</tbody>
</table>
Fewer cells in the cylinder to compensate the increase due to Overset regions
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# LES-PIV COMPARISON (STAR-CCM+ AND STAR-CD)

## Comparison among:

- **PIV** experimental data
- **STAR-CD** 42 cycles
- **STAR-CCM+** 20 cycles

## Compared results

- **LES Quality Estimators**
- **Vector Field of averaged & RMS Velocity**
- **Vector Alignement**
- **Plane XZ (Y=0) valves plane**
- **Plane YZ (X=0) spark plane**

## Analyzed Crank Angles

- 245
- 475
- 540
- 630
Mesh Quality Estimators

**Estimator 1**

\[ M(x, t) = \frac{k_{res}(x, t)}{k_{res}(x, t) + k_{sgs}(x, t)} \]

where

\[ k_{sgs} = 2C_i \Delta^2 \| s_{ij} \|^2 \]

\( M(x, t) \) close to 1: all turbulence scales resolved, conceptually similar to DNS

\( M(x, t) \) close to 0: turbulence scales obtained from SGS, similar to RANS

**Estimator 2**

\[ IQ_v = \frac{\nu_t(x, t)}{\nu(x, t) + \nu_t(x, t)} \]

where

\( \nu_t \) Turbulent Viscosity

\( \nu \) Molecular Viscosity

The lower the estimator value, the better is the LES quality
LES-PIV COMPARISON (STAR-CCM+ AND STAR-CD)

Estimator 1

245CA

STAR-CD

STAR-CCM+

475CA

STAR-CD

STAR-CCM+

540CA

STAR-CD

STAR-CCM+

630CA

STAR-CD

STAR-CCM+

Y=0

1.0

0.90

0.80

0.70

0.60

0.50

0.40

0.30

0.20

0.10

0.0

1.0

0.90

0.80

0.70

0.60

0.50

0.40

0.30

0.20

0.10

0.0
LES-PIV COMPARISON (STAR-CCM+ AND STAR-CD)

Estimator 2

245CA
STAR-CD  STAR-CCM+

475CA
STAR-CD  STAR-CCM+

540CA
STAR-CD  STAR-CCM+

630CA
STAR-CD  STAR-CCM+

Y=0
LES-PIV COMPARISON (STAR-CCM+ AND STAR-CD)

Vector Field comparison

<table>
<thead>
<tr>
<th>PIV</th>
<th>STAR-CD</th>
<th>STAR-CCM+</th>
</tr>
</thead>
</table>

245CA

Y=0

[Graph showing vector fields for PIV, STAR-CD, and STAR-CCM+]
LES-PIV COMPARISON (STAR-CCM+ AND STAR-CD)

Vector Field comparison

PIV

STAR-CD

STAR-CCM+

475CA

Y=0

X=0
Vector Field comparison

LES-PIV COMPARISON (STAR-CCM+ AND STAR-CD)

PIV

STAR-CD

STAR-CCM+

Y=0

540CA

630CA

0.0000

2.5000

5.0000

7.5000

10.000

12.500

15.000

17.500

20.000
A vector alignment parameter is introduced:

\[
\frac{\vec{A} \cdot \vec{B}}{\| \vec{A} \| \cdot \| \vec{B} \|} = \frac{\| \vec{A} \| \cdot \| \vec{B} \| \cos(\alpha)}{\| \vec{A} \| \cdot \| \vec{B} \|} = \cos(\alpha) \in [-1, 1]
\]

being \( \vec{A}, \vec{B} \): velocity vectors associated to the LES (averaged on all cycles) and PIV fields.
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Why STAR-CCM+ and Overset

- Advantages in Scalability

- Possibility to use higher order numeric schemes: MUSCLE 3rd order, which allows to obtain accurate results using a coarser grid: all the main turbulent structures are sufficiently well resolved, a good correspondence with PIV data is shown and LES quality (assessed with Estimators 1 and 2) is comparable with the one obtained with STAR-CD using nearly 2x cells
Mass Conservation

➢ Last year

Mass conservation error 2.6%

➢ Now

Mass conservation error ≈0.1%

Further reduction possible by reducing grid size
**CONCLUSION AND FUTURE DEVELOPMENTS**

**Current Developments**

Effects of finer grids: polyhedral mesh, number of in-cylinder cells at BDC: $2.3 \times 10^6$

**Future Developments**

**O.M.E.L.E.T.T.E. project**

Overset MEsh for LEs investigation of Turbulence in a Transparent Engine

Application of Overset Mesh to TCC for 60/100 cycles using refined grids with different topology (polyhedral / tetrahedral)

**Starting from summer 2017**
I have not failed. I’ve just found 10,000 ways that won’t work.

Thomas A. Edison