USING NUMERICAL SIMULATIONS TO PREDICT AND UNDERSTAND CCV

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OUTLINE

 Background and Motivation
 Parallel Perturbation Model (PPM) Approach
 CCV of PFI Engine using PPM LES
 Comparison of Consecutive LES and PPM LES
 Summary
MOTIVATION

- Cycle-to-cycle variability (CCV) – detrimental to IC engine operation, and results in partial burn, misfire and knock

- Numerically predicting CCV is challenging for 2 key reasons:
  - High-fidelity methods required to capture the turbulent flowfield
  - CCV is experienced over long timescales (1000s of engine cycles)

- CFD techniques for capturing CCV requires high fidelity in:
  - Resolving all relevant length scales – use of LES
  - Modeling the spray structure and realization-to-realization differences
  - Modeling the spark discharge and ignition kernel development

- Long time-scale
  - 1000s of consecutive cycles
  - Simulation time using traditional LES approach is of the order of months
  - Infeasible to be used in the engine design cycle

- Parallel Perturbation Model (PPM): Dissociate the long timescale simulation into several shorter timescale simulations
PARALLEL PERTURBATION MODEL (PPM)

- Each parallel simulation starts from the top dead center of compression. At this crank angle, both valves are closed and the turbulence is almost homogenous.
- The mapped initial condition is obtained from the velocity field at the end of cycle 2.
- The initial conditions for each of the parallel simulations is obtained by adding synthetic turbulent flowfields to the mapped initial condition.
- The length scales and velocity scales of this synthetic field is determined based on the PIV dataset at TDC.

VALIDITY OF PPM LES - RECAP

Motored TCC Engine

- Remarkable agreement in the mean velocities
- RMS velocities show minor differences
- Perturbation methodology and PPM LES approach is reasonable to capture CCV
- The turnaround time reduces from 3 months (consecutive LES) to 10 days (PPM)

Four-cylinder SI engine with port fuel injection (PFI)
Two intake and two exhaust valves per cylinder.
In-cylinder pressure is measured for 1000 consecutive cycles for both cases
Consecutive cycle LES was performed for Case A.
100 parallel cycles simulated for Cases A and B
## LES SETUP

<table>
<thead>
<tr>
<th>Code</th>
<th>CONVERGE v2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational Grid</td>
<td>3D, structured with Adaptive Mesh Refinement</td>
</tr>
<tr>
<td>Spatial Discretization</td>
<td>2\textsuperscript{nd} order, finite volume</td>
</tr>
<tr>
<td>Computational Grid Size</td>
<td>0.7 mm in cylinder &lt;br&gt; <strong>Minimum cell size:</strong> 0.175 mm</td>
</tr>
<tr>
<td>Peak Cell count</td>
<td>7 million</td>
</tr>
<tr>
<td>Time Discretization</td>
<td>PISO (Pressure Implicit with Splitting of Operators)</td>
</tr>
<tr>
<td>Subgrid-scale Model</td>
<td>1-Eq. Dynamic Structure</td>
</tr>
<tr>
<td>Combustion Model</td>
<td>G-Equation</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>36 hours per cycle on 96 cores of LCRC cluster &lt;br&gt; 50 consecutive cycles and 100 parallel cycles are simulated</td>
</tr>
</tbody>
</table>
CONSECUTIVE LES RESULTS
High Cycle vs Low Cycle
CAN PPM BE APPLIED FOR FIRED ENGINES?

CFD Evidence

- Previous study from our group* performed LES of 50 consecutive cycles for Case A and validated the results with experiments.
- They demonstrated that cycle-to-cycle variations in the in-cylinder flowfield and turbulence was the major cause for the simulated CCV.
- They also showed that cyclic variations in the composition field had negligible influence on CCV.
- The PPM approach worked very well in predicting the CCV in the flowfield for the motored TCC engine.
- This gives justification to extending the parallel methodology to the fired PFI engine.

PPM FOR FIRED PFI ENGINE

- Simulations are started at 2160 degrees (TDC of cycle 3) by adding perturbations to the initial flowfield
- The length and velocity scales of these perturbations are determined based on the clearance height and mean piston speed respectively
- 100 simulations are performed till 2920 degrees (40 degrees after TDC of cycle 4)
- On a computing cluster, each cycle requires about 3 days on 96 processors
- The turnaround time for simulating 100 PPM LES cycles is limited only by the availability of computing resources
- The 50 consecutive LES cycles took more than 3 months of simulation time on 96 cores
CONSECUTIVE LES VS PPM
Flowfield statistics at 1 degree before spark (Case A)

- The flowfield statistics are obtained from 49 consecutive cycles and 49 parallel cycles
- Excellent agreement in the mean velocity distributions between the two approaches
- Slight differences in the RMS velocity distributions
CONSECUTIVE LES VS PPM

Equivalence ratio statistics at 1 degree before spark (Case A)

- The mean equivalence ratio shows a stratified structure although this is a PFI engine
- Excellent agreement in the mean equivalence ratio distributions between the two approaches
- Noticeable differences in the RMS distributions
CONSECUTIVE LES VS PPM LES

CCV of In-cylinder Pressure (Case A)

- The in-cylinder pressure from both consecutive LES and PPM are similar to the experimental pressure traces.
- COV of maximum pressure from experiment: 7.64%
- COV of maximum pressure from consecutive LES: 10.45%
- COV of maximum pressure from PPM LES: 9.17%
EFFECT OF OPERATING CONDITION

PPM LES of Case B

- PPM LES was also performed for the low-CCV operating condition Case B
- 100 parallel cycles were simulated
- Reasonable agreement between the experimental and CFD pressure traces
- COV of $P_{\text{max}}$ from Experiment: 4.14%
- COV of $P_{\text{max}}$ from PPM LES: 5.99%

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>r/min</td>
<td>2500</td>
<td>4000</td>
</tr>
<tr>
<td>IMEP (bar)</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>Fueling (mg/cycle/cylinder)</td>
<td>34.1</td>
<td>26.2</td>
</tr>
<tr>
<td>Spark timing (degrees)</td>
<td>711</td>
<td>694.5</td>
</tr>
<tr>
<td>Injection timing (degrees)</td>
<td>340</td>
<td>340</td>
</tr>
</tbody>
</table>
The PPM LES is able to accurately predict the trends in COV with changing operating conditions.

<table>
<thead>
<tr>
<th></th>
<th>Exp</th>
<th>LES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>7.64%</td>
<td>9.17%</td>
</tr>
<tr>
<td>Case B</td>
<td>4.14%</td>
<td>5.99%</td>
</tr>
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</table>
SUMMARY

- Our previous study using the GM TCC engine showed that PPM LES can capture the CCV of gas-exchange well and reduce the computational cost by at least an order of magnitude.
- The PPM methodology was extended to a fired PFI engine.
- This approach shows similar CCV in peak pressure, IMEP and burn-rate parameters as that of the consecutive cycle LES approach.
- PPM LES methodology is able to predict the trends in change of COV with change in operating conditions.
- The wallclock time for PPM LES is **10 times shorter**.
- The turnaround time for the PPM4CCV approach is only limited by the number of available computing cores and is significantly shorter than the consecutive cycle approach.
ACKNOWLEDGEMENT

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- Computing Resources – Argonne ALCF/LCRC
- ANL: Janardhan Kodavasal, Ahmed Abdul Moiz
- MTU: Emma Zhao (Intern at ANL)
- GTI: Navin Fogla, Mike Bybee, Syed Wahiduzzaman
- Politecnico di Torino: Mohsen Mirzaeian, Federico Millo
CCV LITERATURE FROM ANL


THANK YOU

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BACKUP SLIDES
CAN PPM BE APPLIED FOR FIRED ENGINES?

Experimental Evidence

- No apparent correlation between consecutive cycles
- Similar behavior observed for peak pressure as well
- Measurements for Case B also showed similar behavior
- This shows that these are relatively stable operating points and the CCV is driven by stochastic factors
- Parallel Perturbation Model (PPM) may be feasible under these conditions
PERTURBING THE INITIAL CONDITIONS

- 128 parallel simulations were run simultaneously on MIRA supercomputer for 2 consecutive cycles each
- The wallclock time is ~60 hours per cycle on 64 cores on MIRA
- Including wait time, simulating 2 cycles of 128 parallel simulations took approximately 10 days on MIRA.
CAUSES OF CCV

- Potential causes of CCV
  - Composition inhomogeneity
  - In-cylinder flow variations (bulk flow and turbulence)
  - A combination of the two

- Which of the two effects is dominant?
  - This can be investigated by decoupling the flow and composition field.

- In order to answer the questions, we undertook the following numerical experiments:
  1. Swap the composition fields of cycle 4 and cycle 5 before spark and re-run the cycles
  2. Swap the velocity fields of cycle 4 and cycle 5 before spark and re-run the cycles

- If variation in equivalence ratio is the cause of cyclic variation, exercise 1 should cause the cycles to interchange behavior.

- If variation in in-cylinder turbulence is the cause of cyclic variation, exercise 2 should cause the cycles to interchange behavior.
- Cycle 4 (fast cycle) was re-run by replacing the species concentrations with those from cycle 5.
- Cycle 4 remains the fast cycle even after swapping the composition field.
- The composition at spark timing has a low effect on the CCV of the pressure.
Cycle 4 (fast cycle) was re-run by replacing its velocity field with those from cycle 5.
Cycle 4 is now comparable to cycle 5 after swapping the velocity fields.
The velocity field at spark timing has a stronger effect on the CCV of the pressure.
GRID SETUP

Crank angle = 716 deg. (4 deg. BTDC; 5 deg. after spark timing)

- Each cycle was optimized to take about 1.5 days on 64 processors
- Peak cell counts:
  - 8 million during intake
  - ~2 million during combustion
- G-equation coupled with LES
- No detailed chemistry combustion model so soot cannot be captured
CONSECUTIVE LES VS PPM LES

Trapped Mass (Case A)

- Trapped mass from 50 consecutive LES cycles and 50 PPM LES cycle
- The mean trapped mass:
  - Consecutive LES: 590.3 mg
  - PPM LES: 589.8 mg
- Standard deviation of trapped mass:
  - Consecutive LES: 0.537 mg
  - PPM LES: 0.387 mg
- Both approaches predict minimal CCV in trapped mass
The two approaches show excellent agreement in predicting the mean and standard deviation in Y-tumble ratio.

- Similar observations for swirl ratio and X-tumble ratio as well.

\[ T_y = \frac{H_y}{2\pi M_y \omega} \]
CONVERGENCE OF PPM LES

- Ameen et al (IJER 2017) examined the convergence of the flowfield statistics with respect to the number of cycles performed for each condition with the PPM LES calculations.
- It was shown that simulating 2 consecutive cycles for each of the PPM LES calculations were sufficient to obtain convergence of flowfield statistics.
- In the current study, 2 consecutive cycles were performed for each of the PPM LES simulations; COV was computed based on the second cycle.
- To examine the convergence of the PPM LES statistics, 50 additional PPM LES calculations were performed for Case B in which three consecutive cycles were simulated for each simulation.
CONVERGENCE OF PPM LES

COV of Pmax and CA10-75

- Both the cycles converge to the same COV values
- PPM LES approach attains convergence at 2 consecutive cycles per simulation
MACHINE LEARNING ANALYSIS
Identifying and Ranking the Causes of CCV

- A random forest ML model was trained on the simulated cycles
- This model was used to identify and rank the key causes for CCV
- 10 key metrics were chosen and the effects of these metrics on the peak cylinder pressure (PCP) were ranked
- These metrics are related to the velocity field prior to spark timing and the flame topology at 7220

Courtesy: Janardhan Kodavasal, ANL
The random forest model was used to predict the PCP using just 4 key metrics - sphericity, U5.5mm, W5.5mm, COMoX.

The trends are captured well.

Courtesy: Janardhan Kodavasal, ANL