Comparison of a Structured-LES and an Unstructured-DES Code for Predicting Combustion Instabilities in a Longitudinal Mode Rocket

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Outline

• Introduction
• Results – Unstable operating point
• Results – Stable operating point
• Summary and Conclusions
Combustion instability is an organized, oscillatory motion in a combustion chamber sustained by combustion.

Irreparable damage can occur in less than 1 second.

Cl caused a four year delay in the development of the F-1 engine used in the Apollo program
> 2000 full scale tests
> $400 million for propellants alone (2010 prices)

“Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs”
Longitudinal Experiment

Continuously Varying Resonance Chamber

Oxidizer: decomposed hydrogen peroxide
Fuel: gaseous methane

Yu et al. 2013

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Experimental Results

**Unsteady pressure for a translating test**

**PSD power for the first mode**

Unstable Marginally Stable

Harvazinski et al. 2013

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Instability Mechanism

Flow Disruption

Heat Release Moves Downstream

High Pressure Wave

Unburnt Accumulated Fuel

Combustion Reinitiated from Returning Post Wave

Unstable: Cyclic Fuel Disruption and Heat Release

Marginally Stable: Continuous Heat Release

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### Complementary Codes

**Exercised Code Options:**

<table>
<thead>
<tr>
<th>LESLIE</th>
<th>GEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structured</td>
<td>Unstructured</td>
</tr>
<tr>
<td>Explicit MacCormack</td>
<td>Implicit Dual-Time</td>
</tr>
<tr>
<td>LES</td>
<td>DES</td>
</tr>
</tbody>
</table>

Laminar Combustion Closure

Second Order Accurate in Time & Space

- Choked inlet slots have been ignored
- 2-Step reduced mechanism
- LES: 7.3/7.6M
- DES: 3.6/4M

![Diagram showing Mass Flow BC and Adiabatic Walls](image)

Supersonic Outflow

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Modified Wilcox $k$-$\omega$

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial \rho \tilde{u}_j k}{\partial x_j} = \tilde{\tau}_{ij} \frac{\partial \tilde{u}_i}{\partial x_j} - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_k \rho k \right) \frac{\partial k}{\partial x_j} \right]
\]

\[
\frac{\partial \rho \omega}{\partial t} + \frac{\partial \rho \tilde{u}_j \omega}{\partial x_j} = \frac{\gamma \omega}{k} \tilde{\tau}_{ij} \frac{\partial \tilde{u}_j}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_\omega \rho k \right) \frac{\partial \omega}{\partial x_j} \right]
\]

The eddy viscosity is reduced by modifying the turbulent length scale

\[
L_T = \frac{\sqrt{k}}{\beta^* \omega}
\]

\[
\beta^* k \omega = \frac{k^{3/2}}{L_T^*}
\]

\[
L_T^* = \min (L_T, C_{\text{DES}} \Delta)
\]
LES Turbulence Model

Solve a transport equation of the sub-grid kinetic energy

\[
\frac{\partial \rho k^{\text{sgs}}}{\partial t} + \frac{\partial \rho \tilde{u}_i k^{\text{sgs}}}{\partial x_i} = -\tau_{ij}^{\text{sgs}} \frac{\partial \tilde{u}_i}{\partial x_j} - C_{eP} \left( \frac{(k^{\text{sgs}})^{3/2}}{\Delta} \right) + \frac{\partial}{\partial x_i} \left[ \left( \frac{\bar{\rho} \nu T}{\sigma_k} + \mu \right) \frac{\partial k^{\text{sgs}}}{\partial x_i} + \frac{\bar{\rho} \nu T R}{Pr_T} \frac{\partial \tilde{T}}{\partial x_i} \right]
\]

Eddy viscosity is found using a constant model

\[
\nu_T = C_\nu \Delta \sqrt{k^{\text{sgs}}}
\]

Standard gradient diffusion hypothesis closures

\[
\tau_{ij}^{\text{sgs}} = \bar{\rho} \nu_T \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} - \frac{2}{3} \frac{\partial \tilde{u}_k}{\partial x_k} \right) + \frac{2}{3} k^{\text{sgs}} \delta_{ij}
\]

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Unstable Operating Point

DES

Mean Pressure – 1.5 MPa

LES

Mean Pressure – 1.7 MPa

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Fluctuating Pressure

Comparable amplitude and frequency

DES reaches a limit cycle faster

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The phase difference between the head end and the downstream end is captured.
## Integrated PSD Data

<table>
<thead>
<tr>
<th>Mode</th>
<th>Experiment</th>
<th>DES</th>
<th>LES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$1324$ Hz</td>
<td>$387.15$ kPa</td>
<td>$1500$ Hz</td>
</tr>
<tr>
<td>2</td>
<td>$2655$ Hz</td>
<td>$89.29$ kPa</td>
<td>$3050$ Hz</td>
</tr>
<tr>
<td>3</td>
<td>$3979$ Hz</td>
<td>$46.37$ kPa</td>
<td>$4550$ Hz</td>
</tr>
<tr>
<td>4</td>
<td>$7940$ Hz</td>
<td>$41.97$ kPa</td>
<td>$5700$ Hz</td>
</tr>
<tr>
<td>Σ</td>
<td>$564.78$ kPa</td>
<td>$471.533$ kPa</td>
<td>$589.154$ kPa</td>
</tr>
</tbody>
</table>

Similar frequency predictions, both high relative to the experiment.

Mode 4 is under predicted for both codes.

Higher amplitude for LES for modes 1-3.

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Unsteady Flowfield – High Pressure

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Unsteady Flowfield – Low Pressure

DES

LES

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Heat Release Cycle – Part II

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Fuel Cut Off Event

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Reignition Event

Qualitative agreement with reignition behavior

Accumulated methane in the shear layer in both cases

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Marginally Stable Operating Point

**DES**

**LES**

Mean Pressure – 1.5 MPa

Mean Pressure – 1.7 MPa

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Fluctuating Pressure

Comparable amplitude and frequency

LES shows more variability

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## Integrated PSD Data

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<tr>
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<th>Experiment</th>
<th>DES</th>
<th>LES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f$, Hz</td>
<td>$p'_{ptp}$, kPa</td>
<td>$f$, Hz</td>
</tr>
<tr>
<td>1</td>
<td>1379</td>
<td>121.17</td>
<td>1600</td>
</tr>
<tr>
<td>2</td>
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<td>5.86</td>
<td>3250</td>
</tr>
<tr>
<td>3</td>
<td>6475</td>
<td>16.03</td>
<td>4050</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td></td>
<td>143.06</td>
<td></td>
</tr>
</tbody>
</table>

- **LES Over predicts total amplitude**
- **Both cases severely over predict the second mode amplitude**
- **Frequency differences**

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Unsteady Flowfield – High Pressure

Distribution A: approved for public release; distribution unlimited.
Unsteady Flowfield – Low Pressure

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Both LES and DES are capable of simulating self-excited combustion instability.

Agreement between the simulations and experiments for the unstable case was good.

Cyclic heat release was captured.

LES had a delayed reignition, likely responsible for the higher amplitudes.

Cyclic heat release was captured along with reignition event.

Some differences in predictions are due to differences in the grids.

The marginally stable case proved more difficult.

No apparent winner, both approaches have strengths and weaknesses.