The current study describes two modeling approaches to model an unstable seven element linear array of shear coaxial injectors. The first approach is a reduced model where the driving injectors are replaced with an artificial forcing term. The forcing amplitude can be adjusted so that the effect of the transverse instability on the center study element can be examined parametrically. The second approach models the entire domain, and can capture additional details such as the inter-element interactions and the self-excited nature of the instability. Both sets of results are compared with experimental measurements and used to provide physical insights into the underlying instability mechanisms.
Computational Modeling Approaches for Studying Transverse Combustion Instability in a Multi-element Injector

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Combustion instability is an organized, oscillatory motion in a combustion chamber sustained by combustion.

CI 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)

Irreparable damage can occur in less than 1 second.

Damaged engine injector faceplate caused by combustion instability

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

• Review of single-element simulations
• Multi-element experiments
• Modeling approaches
• Results
  – Approach 1 – reduced model
  – Approach 2 – complete model
• Summary
Single Element Studies

Short Post
Marginally Stable

Intermediate Post
Unstable

Long Post
Stable

Long Post
Unstable

CVRC Experiment
Purdue University

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Instability Mechanism

• A series of 3D simulations for the short, intermediate, and long post lengths was completed to identify the instability mechanism.

• The marginally stable short length showed continuous heat release

• The unstable results were the result of a fuel cut off event.
Instability Mechanism

- For the intermediate length combustion was reinitiated when the returning oxidizer post wave pushed the accumulated fuel into the warm recirculating gases.
Instability Mechanism

- For the long length combustion was reinitiated later in the cycle and was the result of mixing between the recirculating gases and the accumulated fuel
- Simulations only predicted the unstable long length
- Experimentally this length showed the most variability
# Single & Multi-element Studies

<table>
<thead>
<tr>
<th>Single Element</th>
<th>Multi-element</th>
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<tbody>
<tr>
<td>• Less expensive</td>
<td>• More expensive</td>
</tr>
<tr>
<td>• Smaller domains</td>
<td>• Larger domains</td>
</tr>
<tr>
<td>• Substantial work published</td>
<td>• Complex geometries</td>
</tr>
<tr>
<td>• Wall effect is exaggerated</td>
<td>• Less literature, limited work</td>
</tr>
<tr>
<td></td>
<td>• Captures inter-element interactions</td>
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</tbody>
</table>
Transverse Instability Combustor

- Transverse Instability Combustor – TIC
- Experimental rig developed at Purdue University
- Four major iterations to date
- Rectangular chamber with 7 elements
- Linear array of 7 elements
- Injectors are similar to the single element work
- Instability is self-excited

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TIC Configuration

**Dual Purpose Experiment:**

1. Self-excited transverse instability
2. Observe combustion response of the study element to high amplitude transverse instabilities

Injector elements are similar to the longitudinal experiment

½ Wave resonator, Couples with 1T

Study Element

High Freq Pressure Transducers

Optical Access

Tapered Nozzle

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## TIC Experiments

<table>
<thead>
<tr>
<th></th>
<th>TIC 1a</th>
<th>TIC 1b</th>
<th>TIC 1c</th>
<th>TIC 1d</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oxidizer</strong></td>
<td>H_2O_2</td>
<td>H_2O_2</td>
<td>H_2O_2</td>
<td>H_2O_2</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Fuel Driving</strong></td>
<td><strong>Driving</strong></td>
<td><strong>Driving</strong></td>
<td><strong>Driving</strong></td>
<td><strong>Driving</strong></td>
</tr>
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<td></td>
<td>JP-8</td>
<td>RP-1</td>
<td>CH_4</td>
<td>CH_4</td>
</tr>
<tr>
<td><strong>Fuel Study</strong></td>
<td>C_{12}H_{26}</td>
<td>C_2H_6</td>
<td>CH_4</td>
<td>CH_4</td>
</tr>
<tr>
<td><strong>Oxidizer Inlet</strong></td>
<td><strong>Driving</strong></td>
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<td><strong>Driving</strong></td>
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<td>Perforated Plate</td>
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<td>Perforated Plate</td>
<td>Choked Venturi</td>
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<tr>
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<td><strong>Driving</strong></td>
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</tr>
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<td></td>
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<td>Choked Venturi</td>
</tr>
<tr>
<td><strong>Notes</strong></td>
<td>Two-phase flow</td>
<td></td>
<td>Multiple study ox-post lengths considered</td>
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</tr>
<tr>
<td><strong>Companion Simulations</strong></td>
<td>3-element</td>
<td>7-element</td>
<td>Future Work</td>
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</tr>
</tbody>
</table>

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Amplitude Control – TIC 1a&b

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Amplitude Control – TIC 1c&d

- Length of the study element proved to be largely unimportant
  - Low < 170 kPa
  - High > 680 kPa

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Two Distinct Modeling Approaches

Full Simulation

• Captures self-excited instability
• Captures inter-element interactions
• Amplitude is difficult to control
• Expensive

Reduced Model

• Does not capture driving
• Limited inter-element interactions
• Amplitude is prescribed
• Low cost
Virtual Injector Screening Tool

- The reduced model can be used as a virtual injector screening tool
- The element of interest is subjected to forcing and the response is observed
- An artificial boundary condition is used to drive the instability

\[ u_{\text{wall}} = A \sin(2\pi f + \phi) \]
Amplitude Control

- The amplitude is tunable

![Graph showing amplitude control](image)

**Targeted Amplitude**

**Observed Wall Pressure**

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An excellent comparison to the experimental results can be achieved by prescribing a single sine wave.
Observer the effect of transverse oscillations on the study element

Unsteady Pressure at the Side Wall

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Heat release oscillates with pressure wave.

Acoustic coupling visible in the side elements.

Temperature in the side region is artificially high from the imposed boundary condition.
Seven Element Simulation

- Considerably more expensive based on the added grid points for the additional elements
- Simulation captures the self-excited nature of the experiment, inter-element interactions
Self-excited Simulation

Can be used to test:
- Self-excited simulations
- Element to element interaction
- Element to wall interaction

Captures initial transient which includes a period of low instability before transitioning to high amplitude instability

Coupling between driving injectors and main chamber

Pressure Pa
- 1.2E+06
- 1.15E+06
- 1.1E+06
- 1.05E+06
- 1E+06
- 950000
- 900000
- 850000
- 800000
- 750000
- 700000

Pressure fluctuations, kPa
- 1000
- 500
- 0
- -500

Time, s
- 0
- 0.005
- 0.01
- 0.015
- 0.02
- 0.025

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Inter-element Interactions

- Shed vortex
- Delayed heat release
- Transverse wave increase inter-element interaction
- More heat release when the pressure is high
- Increased vorticity at the wall from impingement
Summary

• Two modeling approaches were presented for modeling transverse instability along with a sample result of each

• Virtual injector screening tool
  – Observe the injectors response to excitation in a controlled environment
  – Precise control of amplitude, frequency

• Full Simulation
  – Captures self-excited transverse instability, inter-element interactions
  – Coupling between injectors and the main chamber
Future Work

• Modeling TIC 1d
  – Attempting to capture what happens when the length of all injectors are changed
  – Preliminary experimental suggest that different amplitude are obtainable
  – The unstable single element length showed stable combustion in the transverse chamber! This is unlike prior results.