Combustion instabilities have been observed in nearly every major liquid rocket engine development effort, including the most recent development programs. They are caused by the coupling of the natural acoustic modes of the combustion chamber with the dynamics of the heat release, which can in turn lead to catastrophic damage of the internal components of the rocket engine. Rayleigh's criterion states that combustion instabilities are driven when the pressure waves and the heat release are in phase and that the instabilities are damped when they are out of phase. Despite the simplicity of this relationship, the prediction of the occurrence of combustion instabilities has proven to be an enduring challenge because of the inherent complexities in the physics of multiphase turbulent flames. The Air Force Research Lab (AFRL)'s Advanced Liquid Rocket Engine Stability Technology (ALREST) program is a coordinated effort that involves both modeling and experimental components at various universities, small business, industry and in-house. The overall approach is to conduct data-centric, multi-fidelity combustion stability model development. "Data-centric" means that all model development is directed at experimental data sets. "Multi-fidelity model development" means that the most effective way to advance modeling capability is to do it simultaneously at multiple levels of fidelity. The talk will focus particularly on the modeling efforts of two experimental datasets obtained at Purdue University, which involve Detached Eddy Simulations of the turbulent reacting flowfield are shown to be effective in predicting the instability phenomena and the associated trends. In addition, the talk will also provide a general overview of rocket propulsion activities at AFRL.
Progress and Challenges in Liquid Rocket Combustion Stability Modeling

Dr. Venke Sankaran AFRL/RQ

NASA Ames Research Center

4 Dec 2012

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Air Force Research Lab

Air Force Research Laboratory

- 10 Major R&D sites across US
- 40 Locations around the World
- 10 Technical Directorates
  - Air Vehicles (RB)
  - Propulsion (RZ)
  - Aerospace Systems Directorate (RQ)

- 5,400 Gov’t Employees
- 3,800 On-site Contractors
Facilities

**Bench-level Labs**

**High Thrust Facilities**
- 19 Liquid Engine stands, up to 8,000,000 lbs thrust
- 13 Solid Rocket Motor pads, up to 10,000,000 lbs thrust

**Altitude Facilities**
- From micro-newtons to 50,000 lbs thrust
Programs of Interest

USET – Upper Stage Engine Tech,
IMLM – Integrated Motor Life Management
MCAT – Material Component Applications Tech

HC Boost – Hydrocarbon Boost
AFM 315E – Green Propellant,
EP – Electric Propulsion
USET
(Upper Stage Engine Technology Program)

- Validating new suite of LOx/Hydrogen rocket engine M&S tools through heavily-instrumented 4,000 hp, 90,000 rpm turbopump
- Risk reduction work ups TRL of components allowing SMC/LR NGE program to enter post-milestone B, saving years on the schedule and $multi-M’s in cost
- Verify and Validate suite of tools to greatly reduce the amount of physical testing by conducting better M&S during design to eliminate large amounts of testing
- NGE with SMC/LR and tools used in current NGE risk reduction work, Hydrocarbon Boost, >45 M&S tool-specific transitions to industry, DOD, NASA

In-House:
- Test stand Buildup
  - Design of new facility hardware
  - Hardware Fabrication
  - Hardware Installation
- In-house tool validation and verification
- On-site rapid data reduction and analysis

The WOWs:
- SMC/LR requested TTP transition to NGE
- Key member of AUSEP (Affordable Upper Stage Engine Program) IPT
- Conducted Risk Reduction work on USET contract to support AUSEP TRL requirements
- Most highly instrumented, highest tip speed and suction of any turbopump ever tested

Program Completed, Report in Progress
# HC Boost
(Hydrocarbon Boost Program)

**In-House:**
- Building subscale test facility to mitigate combustion devices risk
- Critical combustion research using 219 funds
- Fuel thermal stability, nozzle cooling, injector design

**The WOWs:**
- Design, build, test ORSC LOx/Kerosene Liquid Rocket Engine Tech Demonstrator
- ORSC is a higher performing engine resulting in a smaller launch vehicle or an increase in delivered payload

**HCB establishes advanced, modern, domestic LRE Tech Base**
- 1st reusable high performance U.S. HC engine
- Establishes Ox-rich staged combustion (ORSC) tech base for U.S.
- Help sustain ailing U.S. rocket engine industry tech development base
- HCB strongly supports SMC/LR American Kerosene Engine project
IMLM
(Integrated Motor Life Management)

Goals: Reduce predictive uncertainty of future state of a motor on an individual basis by 20%/50% (near/far term goals)

In-House:
• Validation of A&S modeling capability
• AFNWC funded supported for ANDES improvement (Automated NDE Data Evaluation System)
• ICBM Program Office bringing A&S analysis capability in-house

The WOWs
• Potential to provide millions in cost avoidance
• Provide accurate near real-time motor health condition (diagnostics)
• Provide individualized service life estimates (prognostics)
• Transition opportunity ~ 2018

First integration of motor specific sensor data to advanced aging models to provide a individualized service life estimate

Sensors to include: temperature, humidity, case damage, propellant slump, acceleration, and TVA displacement and load

Data processing and storage

Analysis

Command & control
What are we doing? Developing new solid rocket motor (SRM) components and M&S that decrease inert weight by 20%.

Customer why? High-speed penetrator weapons will enable attack of deeply-buried targets.

Tech Reason? New M&S tools may enable higher efficiencies from SRM designs.

Transition? 3 of 6 FY12 task orders support an AFRL FCC. 1 of 6 FY12 task orders supports AFNWC In-House: Experiments to validate new models

The WOWs

- The AFNWC propellant task is part of a plan that may save $2.1B in future acquisition costs
Electric Propulsion

What are we doing? Developing new technologies that enable less expensive, more maneuverable and more agile s/c

Customer Why? Reducing launch mass substantially reduces launch cost, increases payload fraction, and enables missions otherwise not possible (e.g. AEHF)

Tech Reason? Plasma propulsion increases Isp by 10x, reducing s/c propellant 10x, enabling lighter and/or more capable s/c

Transition?
• Tech demos: FalconSat-5—demonstrating low power propulsion and spacecraft impact
• Operational systems: AEHF—enabling high mass spacecraft directly supporting warfighter

In-House:
• Test facilities
  • 8 vacuum chambers
• Thruster design
• Diagnostics
• Validation of M&S
• Mod/Sim Program
• Dedicated staff
• Advanced numerical methods

The WOWs:
• AEHF requested assistance with thruster performance verification; SV-2 onboard diagnostics package flying right now
• Developed propulsion module for FalconSat-5 tech demo, including spacecraft interaction diagnostics
• Cubesat EP propulsion module selected by 2 constellations for flight in 2014
• National M&S effort for EP coordinated by AFRL-RZSS
AFRL Developed Advanced Monopropellants

What are we doing? Providing advanced propellant with higher performance and much lower toxicity than hydrazine.

Customer why? Faster operational response with reduced costs can be attained with greater mission capabilities.

Tech Reason? Energetic ionic liquids provide low vapor toxicity and high energy density.

Transition? Orbital flight experiment on TBD S/C-2014

In-House:

- Fully characterized small scale safety & hazard properties
  - Passes all safety requirements
  - DOT approval for transport
- First successful thruster firings
- Pilot scale propellant production
  - Advanced monopropellant cost = hydrazine cost
  - Supplying transition programs

Advanced monoprops can perform like bipropellant in small craft!
Combustion Instability

• Combustion instability occurs when the combustion dynamics couple with the combustion chamber acoustics

• Irreparable damage can occur in <1s

• Combustion instability 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 (at 2010 prices)

• CI has been identified as a major risk factor in AFRL’s Hydrocarbon Boost program.

“Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs” – JANNAF Stability Panel Draft (2010)

Damaged F-1 engine injector faceplate due to combustion instability
Rayleigh Criterion

\[ R = \frac{1}{t_f - t_0} \int_{t_0}^{t_f} \left( \frac{\int_\Omega (p(x, t) - \bar{p}(x)) \, d\bar{x}}{\int_\Omega \bar{p}(x) \, d\bar{x}} \right) \left( \frac{\int_\Omega (q(x, t) - \bar{q}(x)) \, d\bar{x}}{\int_\Omega \bar{q}(x) \, d\bar{x}} \right) \, dt \]

• Stated by Lord Rayleigh in 1878
  – Defines phase relationship between pressure and heat release
    • A positive value indicates that they are in phase and are driving the instability
    • A negative value indicates that they are out-of-phase and are damping the instability

• Coupling relationship is very complicated
  – Controlled by acoustic interactions with sub-processes like injection, atomization, vaporization, mixing and combustion
High Pressures

• Rocket Conditions
  – Very high pressures 1000-3000 psi
  – Cryogenic propellants at sub-critical temperatures

• Diagnostics
  – Extremely challenging to obtain detailed data in rocket environments

• Modeling Challenges
  – Multiphase phenomena
  – Extremely high density ratios
  – Wide range of velocity scales
Turbulence and Combustion

• Turbulence
  – Unsteady dynamics requires LES or RANS/LES

• Chemistry
  – Detailed chemical mechanisms for typical hydrocarbon fuels

• Turbulent-Chemistry Interactions
  – Sub-grid chemistry source term closure
Boundary Conditions

• Acoustic Coupling
  – Chamber acoustics couple with oxidizer post and oxidizer and fuel manifolds
  – Need to include full configuration!
ALREST

Advanced Liquid Rocket Engine Stability Technology

• OBJECTIVE

• Develop advanced physics-based combustion stability design tools to reduce the risk of developing combustion instabilities in future Air Force liquid rocket engine development programs

• APPROACH

• Conduct data-centric, multi-fidelity model development in coordination with other national efforts
Data-Centric Model Development

Experiments

- Spinning CI
- Longitudinal CI
- Standing CI
- Driven jets

Full Scale (existing and HCB)

HCB will be heavily instrumented to provide CI data

Andersson (Purdue)
- AFOSR
- NASA CUI P
- ALREST
- AFRL

Frederick (UAH)
- NASA CUI P
- AFRL
- ALREST

Karagozian (UCLA)
- AFOSR
- ALREST

Leyva, Talley (AFRL)
- AFOSR
- ALREST

Cavitt (Orbitec)
- AFRL
- ALREST

Santoro (PA State)
- AFOSR (core)
- NASA CUI P
- ALREST

Yu (Maryland)
- NASA CUI P

Zinn (GA Tech)
- AFOSR

Nestleroad Engin’ng
- MDA
Multi-Fidelity Model Development

Models

- Increased Fidelity
  - Experiments
    - Full physics to understand mechanisms and derive response functions
    - e.g., Hybrid RANS/LES
    - URANS with response functions and detailed geometries
    - e.g., URANS
    - Analytical Solution
      - e.g., Linear Euler
    - Generalized Instability Model
      - e.g., Galerkin Series Expansion

- Increased Cost
  - ALREST-HFM
  - ALREST
  - Response Functions
    - ALREST

Near term spinoffs

- Flandro (GTL)
  - OSD, AFRL
- Heister (Purdue)
  - AFOSR, NASA
- Merkle (Purdue)
  - NASA, AFRL, AFOSR, ALREST
- Muss (Sierra)
  - AFRL
- Palaniswamy (Metacomp)
  - AFOSR, AFRL, MDA ALREST
- Yang (PA State)
  - AFOSR, AFRL, MDA
- Bellan (JPL)
  - AFOSR
  - ALREST
- Kassoy (U. Colo.)
  - AFOSR
  - ALREST
- Priem consultants
  - ALREST
- Menon (GA Tech)
  - ALREST, AFOSR
- Munipalli (HyPerComp)
  - ALREST
- Sirignano, Sideris (UC Irvine)
  - AFOSR
  - Lynch (PWR)
  - ALREST
Source code will be delivered and maintained by Hypercomp after the contract ends.
ALREST Validation Cases

Hydrogen Stable Single Element (PSU) -> Supercritical Non-reacting (AFRL) -> Stable Single Element Methane (Singla)

Unstable Longitudinal Methane Single Element (Purdue) -> Transverse single elem. hydrocarbon (Purdue, UAH) -> Transverse few elem. Hydrocarbon (Purdue, Orbitec, GA Tech)

“Final Exam”

82-Element Methane Stable & Unstable (Jensen) -> Engine Chamber Conditions with RP/LOX (HCB)
Longitudinal Stability Chamber

Purdue’s Continuously Varying Resonance Chamber

[Diagram of the Longitudinal Stability Chamber with labels for various components such as Linear Actuator, Translating Shaft, Gas Generator, Ox. Injector, High Frequency Pressure Transducers, Available Ports for Rear-End Mode Shape Measurements, Nozzle, Modeled Domain, Mean Pressure Measurement, Modular Chamber Sections, Fuel Injector, Oxidizer Post, Fuel Manifold, Ox. Manifold Extension, Rod-End Alignment Coupler, Sliding Seal.]
Sample Experimental Results

Experimental Results – PSD

Purdue University
Sample Experimental Results

1. Pressure - 9.75 in High-Pass Filtered PSD
2. Pressure, 9.75 in High-Pass Filtered PSD
3. Pressure, 5.75 in High-Pass Filtered PSD
4. Pressure, 1.5 in High-Pass Filtered PSD
5. Pressure, 0.5 in High-Pass Filtered PSD
6. Pressure, 0.05 in High-Pass Filtered PSD

PSD between 9.768 and 9.868 Hz; Avg. $L_{op} = 7$ in

$L_{op} = 7.00''$
$L_c = 15.00''$
Sample Experimental Results

![Graphs showing experimental results](image)

**Graph Details**

1. Pressure, -3.5' High-Pass Filtered PSD
2. Pressure, -6.5' High-Pass Filtered PSD
3. Pressure, 1.5' High-Pass Filtered PSD
4. Pressure, 3.5' High-Pass Filtered PSD
5. Pressure, 14.5' High-Pass Filtered PSD
6. PSD between 10.002s and 10.162s; Avg. L_{eq} = 6.51 m

**Dimensions**

- \( L_{op} = 6.50'' \)
- \( L_c = 15.00'' \)
Sample Experimental Results
Sample Experimental Results
Sample Experimental Results

1. Pressure, 3.5" High-Pass Filtered PSD
2. Pressure, 4.5" High-Pass Filtered PSD
3. Pressure, 1.5" High-Pass Filtered PSD
4. Pressure, 2.5" High-Pass Filtered PSD
5. Pressure, 0.5" High-Pass Filtered PSD
6. Pressure, 3.5" High-Pass Filtered PSD

PSD between 10.73 Hz and 10.83 Hz; Avg. L_{op} = 9 in

L_{op} = 5.00"  L_{c} = 15.00"

Purdue University
AFRL
Sample Experimental Results

[Graphs showing experimental results with labels and data points]

[Diagram illustrating experimental setup with dimensions L_{op} = 4.50\,\text{in} and L_c = 15.00\,\text{in}]

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Sample Experimental Results
Computational Results

Mach Number

0.0  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0

Temperature, K

400  800  1200  1600  2000  2400  2800

Heat Release Surface Colored With Pressure

25% CH₄

1.4E+06  1.55E+06  1.7E+06  1.85E+06  2E+06  2.15E+06
Vorticity

3D

Vorticity, 1/s

2D-C

Vorticity, 1/s

2D-F

Vorticity, 1/s

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Pressure Waves

3D Pressure Signal

Experiment

2D - Fine Pressure Signal

2D - Coarse Pressure Signal

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Power Spectra
Mode Shapes

Mode 1

Mode 2

Pressure

Velocity
Instability Mechanism

- High pressure wave in oxidizer post returns half-way through the cycle
- Leads to pinching off of flame that serves as ignition when the high pressure wave returns in combustor
Rich vs. Lean

<table>
<thead>
<tr>
<th></th>
<th>Fuel Rich</th>
<th>Fuel Lean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalence Ratio</td>
<td>1.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Rayleigh Index

Lean

Rich

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Transverse Mode Chamber

Oxidizer Manifold

Fuel Injectors

Optical Access

Converging Nozzle

Ox Ports

Driving Elements

11 High Frequency Pressure Ports

Exhaust
Future Directions

• Turbulent Combustion
  – Linear eddy models
  – Flamelets
  – FMDF models

• Improved Accuracy
  – High-order Cartesian
  – Adaptive mesh refinement

• Improved Efficiency
  – Algorithmic and Scalability Enhancements

• Model Reduction
  – Reduced-order models
  – Reduced-basis models
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