The Direction of Fluid Dynamics for Liquid Propulsion at NASA Marshall Space Flight Center

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Advances in Rocket Engine Modeling and Simulation, and its Future
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FLUID DYNAMIC BRANCH STRUCTURE

Fluid Dynamics Branch
Branch Chief – Lisa Griffin
Deputy Branch Chief – Tom Nesman
Technical Assistant – Denise Chaffee
Computer System Administrator – Dennis Goode

Propellant Delivery CFD
Team Leader: Jeff West

Experimental and Unsteady Flows
Team Leader: Tom Zoladz

Acoustics and Stability
Team Leader: Vacant

Combustion Driven CFD
Team Leader: Kevin Tucker

ER42 is comprised of four teams of approximately forty-five employees
The Fluid Dynamics Branch (ER42) is responsible for all aspects of the discipline of fluid dynamics applied to propulsion or propulsion-induced loads and environments. This work begins with design trades and parametric studies, and continues through development, risk assessment, anomaly investigation and resolution, and failure investigations. Because of the skills in the branch, ER42 also works non-propulsion items such as for telescopes and payload racks on an as needed basis.

**FLUID DYNAMICS ANALYSIS**

**Scaling Methods**

**Gain / Phase Plots**

**System Stability Modeling**

**Lump Parameter Modeling**

**Finite Element Modeling**

**Computational Fluid Dynamics**

**ER42 conducts all levels of fluid dynamics analysis from scaling methods through 3D Unsteady CFD**

**ER42 is a Discipline-Centric branch, not analysis-centric or test-centric. Integration of all discipline methods into one branch enables efficient and accurate support to the projects.**
**FLUID DYNAMICS TESTING**

ER42 conducts and supports testing for hardware and technology development and verification, and analysis validation:
- Primary responsibility for cold flow and scale model acoustics tests
- Secondary responsibility for hot system and component testing

**MAIN PROPULSION SYSTEM**

- The Main Propulsion System (MPS) is defined as the propellant delivery system from Tank to Engine Interface.
  - Tank with all of its internal components
  - Valves
  - Feedlines with all of its internal components
- ER42’s primary analysis tool for MPS is CFD
LIQUID PROPELLANT TANKS - SLOSH

ER42 performs high fidelity CFD analysis of complex geometry and/or complex accelerated propellant tank sloshing to determine slosh modes and their respective frequencies, amplitudes, and damping characteristics.

Improvement to Classic Mass-Spring Model

Next challenges with future simulations include implementation of massively parallel gas-liquid interface tracking methods and efficient hybrid implicit/explicit methods to address disparate time-stepping requirements.

LIQUID PROPELLANT TANKS – PRESSURIZATION AND DRAIN

- Tank Pressurization
  - Flow through diffuser
  - Interaction of ullage gas with propellant surface (mass transfer, multiphase heat transfer, surface evaporation, chemical species)
- Tank Drain
  - Analysis of vortical flow in pipe
  - Assessment of anti-vortex baffle efficiency

Near Term Work
- Validation of robust method for simulating mass transfer across the gas-liquid interface

LH2 Tank Pre-press Analysis
ER42 conducts high fidelity CFD simulations of valves to predict fluid flow patterns, mean pressure drops, and unsteady fluid environments.

Future work aimed at implementation of valve component force and friction models.
**FEEDLINES**

ER42 performs high fidelity CFD simulations of liquid propellant feedlines to predict pressure drops through bends, articulating joints, and splits, flow uniformity due to bends and wakes, and unsteady pressure environments.

**TURBOPUMPS**

ER42 supports the design, development, and certification of high-speed turbomachinery:
- Quick turnaround CFD design parametrics
- Time-accurate rotor-stator CFD analysis
- Highly instrumented pump waterflow test
- Component and engine test support
Unsteady Loads Development

- All flow features which significantly modify fluid forcing functions of interest must be modeled.
- Must show spatial and temporal resolution of unsteady forcing functions.
- Full 360 degrees models are necessary for most rocket turbines due to large regions of separated flow. Periodic models corrupt the unsteady forcing functions and are not sufficient.

Unsteady Loads Delivery

- Unsteady pressure history saved at all points of all blade surfaces Must show spatial and temporal resolution of unsteady forcing functions.
- Unsteady pressure histories from blade surfaces are interpolated onto stress grids for structural analysis. All blades must be used if rotor-rotor or stator-stator effects are to be captured.
- Unsteady pressures may be delivered in temporal or frequency domains.
**TURBINE AIRFLOW TESTING**

Testing of Highly Instrumented Turbine Models in Scaled Air Conditions
- Steady and unsteady pressure loadings
- Interstage cavity pressures
- Performance mapping over a wide range
- CFD validation

Fourier Transforms of First Stage Blade Suction Side at 13% Axial Chord and 50% Span Location

Highly Instrumented Turbine Test Article

**PUMP WATERFLOW TESTING**

2-blade inducer with on-rotor dynamic force measurement system

Low pressure pump with upstream main propulsion system element simulation

Comprehensive steady and unsteady pump performance is evaluated at scaled engine operating conditions. Dense instrumentation suites, velocimetry, and flow visualization are utilized in mapping pump characteristics.
Time accurate CFD provides insight into the complex flow field behind higher order cavitation. Higher order cavitation is a potential forcing function for primary inducer bending modes. CFD calculations effectively capture tip vortex dynamics for inducers operating with minimal tip clearance (without cavitation suppressor).
COMBUSTION STABILITY ASSESSMENT APPROACH &
SKILLS LEVERAGED BY ER42

• Branch asked to assess the combustion
dynamics / stability of an engine design
  • Chug
  • Acoustic
  • Other oscillation modes (e.g., buzz from upstream
    supply system)
• Common to all three generic stability types are
two main assessment questions:
  • What is the margin associated with the stability type?
    • Requires accepted definition of stable, unstable, and
      marginal
  • What margin is acceptable for a given engine design?
• Assessment comes from a combination of two
  approaches:
  • Analytical
    • Linear: system stability approaches; energy based
      approaches
    • Non-linear: limit cycle waveform evaluation
  • Testing
  • Non-linear: waveform characterization of damp times
    and amplitudes

• Skills Required
  • Unsteady Fluid Transients and Dynamics
  • Heat Transfer and Thermodynamics
  • Acoustics
  • System Dynamics and Linear Analysis
    (Stability Theory, State Space, Transfer Matrix)
  • Electronics (Fluid Circuit Analogies, Linear
    Analysis)
  • Mathematics (DDEs, Model Development, Linear
    Analysis)
  • Control Engineering (System Identification,
    Nyquist Plots, Bode Plots)
  • Stability Theory (Nyquist Criterion, et al.)
  • Signal Analysis (Data Characterization and
    Reduction)
  • Instrumentation and Data Acquisition
  • Combustion Devices and Propulsion
  • Combustion Processes (Spray and Flame
    Dynamics, Mixing, Atomization, Vaporization,
    etc.)
COMBUSTION STABILITY ASSESSMENT: EMPIRICAL STABILITY ASSESSMENTS

Example engine test data - 1L mode instability exhibited during testing program
- ~300 – 400 Hz stable to unstable signal
- **New methods created to judge spontaneous stability**
  - Offered new way to approach characterizing signal via statistics and frequency variability
  - Gave metrics on how to divide stable vs. unstable
- **New methods created to judge dynamic stability**
  - Assess statistical character of data prior to bomb
  - Track when amplitudes reach back within ‘statistically significant limits’

COMBUSTION STABILITY ASSESSMENT: ANALYTICAL ASSESSMENTS

Branch analytical models encompass:
- Classical linearized stability models
- Computational Fluid Dynamics (CFD)
- Finite element modeling (FEM)
- Linearized models are used for chug and acoustic mode evaluations
  - State-space and impedance models
- CFD and FEM used to better characterize complex flowfields and geometries
  - Accounts for distribution of fluid properties
  - Coupled acoustic modes better evaluated using CAD geometries and CFD inputs
Objective of Improvements
- Advance the predictive capability of current, state-of-the-practice tools and methodologies used in combustion stability assessments
- Facilitate
  - Confident identification & characterization of combustion instabilities
  - Successful & efficient mitigation during propulsion system development
- Minimize development costs & improve hardware robustness

Approach to Improvements
- Improve state-of-the-practice stability assessment capability by use of higher-fidelity, physics-based information either integrated into the engineering tools or used separately in the assessment process
- Extract physics-based models/information from focused state-of-the-art CFD simulations
- Validate new capability by exercising the improved capabilities on relevant experiments

Rayleigh Index
Oscillation Dec.

COMBUSTION STABILITY ASSESSMENT: IMPROVING THE STATE-OF-THE-ART

Instantaneous 2-D snapshots from a 3-D non-reacting simulation of a gas-centered swirl coaxial element

Pressure in fuel manifold
Density
Mach number

RANS simulation of a reacting like-on-like impinging doublet element

X-Z Planes, Contours of T (K)
LOX
RP1
RP1, Soot and CO near faceplate
Immediately reacts with LOX
(Flowfield is periodic in X and Z)

Larger momentum of LOX jets displaces RP1 jets

Ongoing improvements for injector CFD
- Flamelet formulation for efficient simulation of reacting flows
- VOF & atomization for 2-phase flow
- Low dissipation schemes better resolving turbulence & acoustics

*Courtesy of W. Anderson/Purdue University
SOLID ROCKET MOTOR THRUST OSCILLATIONS: WHY ARE THEY A CONCERN?

• SRM thrust oscillations during flight can deliver forced accelerations to vehicle structure and acoustic mode frequencies
  • Space Shuttle System
  • Arianne 5

• If these forced accelerations match appropriate vehicle structural modes, then vehicle resonance can occur
  • Ares I
**SOLID ROCKET MOTOR THRUST OSCILLATIONS: CFD INPUTS TO INCREASED UNDERSTANDING OF FLOWFIELD**

- (1) Vortex shedding within internal SRM flow field causes pressure perturbations
- (2) Wave generation rate tunes with SRM 1L, 2L, 3L acoustic modes
- (3) 1L, 2L, 3L acoustic mode shapes create subsequent thrust oscillations

**Ongoing Improvements**
- Efficient LaGrangian particle tracking
- 2-phase capability to model slag dynamics
- Acoustic source location and mode extraction from CFD results

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**SOLID ROCKET MOTOR IGNITION**

- The ignition transient is a critical part of motor operation
- Elevated thrust rise rate is too high threatens vehicle structural integrity
- CFD ignition simulation
  - As-cast motor geometry mesh with ~ 150M cells
  - Simulation execution complete on 2400 CPUs in less than 2 weeks
  - Results are being used to help understand test stand dynamics issues

**Pressure field during first ~ 0.6 s of large motor ignition transient**

**CFD results compared to head end pressure trace from static test**

**Ongoing Improvement Efforts**
- Efficient LaGrangian particle tracking
- Propellant grain recession capability to enable appropriate propellant geometry during longer transient simulations
LAUNCH ENVIRONMENTS

1D Linearized Physics Models

ER42 Develops the Fluid and Acoustic Environments for Launch
- Liftoff Acoustics
- Overpressure
- Sound Suppression
- Liftoff Debris Transport
- Hydrogen Entrapment

ER42 Uses Multiple Levels of Analysis and Testing to Accomplish this Work

Flight Tests

Scale Model Tests

CFD

OVERPRESSURE – ANALYTICAL MODEL

Overpressure Predictions Using Analytical Models
- Broadwell & Tsu Model: Linearized 1-D physics-based model for overpressure in a ducted launcher
- 4-wave model: Acoustic modification to incorporate resonant conditions
- Attenuation Model: Empirically based on Shuttle data or other motors/engine correlations
- Knockdown Factors for water suppression or pressure wave diffraction: Empirically-based or CFD simulation-based
- Margin: Technical agreement based on CFD simulations and unknown
- Improvement – Continually improve models based on CFD, Test data, and Flight data

4-Wave Physics Model

Broadwell and Tsu Model Application
CFD has recently shown to represent overpressure very accurately without the inclusion of water
- Demonstrated ability to capture IOP and DOP waves at several locations for dry tests

Provides ability to address limitations of Analytical models
- Accounts for complex flow scenarios and three-dimensional launch pad geometry

Provides parametric studies where unknowns currently exist

Ongoing improvements include modeling water suppression systems, multiphase solid booster effluent, and capture higher frequency spectral content

Comparisons of CFD predictions with ASMAT data
**LIFTOFF ACOUSTICS**

1. **Design New Launch Vehicle**
2. **Derive Liftoff Environments**
3. **Validate Scale Model Acoustic Test**

Liftoff noise is generated by the mixing of rocket exhaust flow with the surrounding atmosphere and its interactions with surrounding launch pad structures.

ER42 creates initial liftoff acoustic environment derived from Saturn V, Space Shuttle flight data, and Ares I-X flight test data, for the development of Ares I and the proof-of-concept vehicle, Ares I-X. Parameters and identification of sources from CFD

Use acoustic scale model test to validate liftoff acoustic environments and water sound suppression system design.

**SCALE MODEL ACOUSTIC TESTING**

- Determine model scale using Strouhal Number
  \[ St = \left( \frac{f_d}{V} \right) = \left( \frac{f_d}{V_t} \right) \]

- Design test article to this scale; fire; acquire data.

- Data Processing

Typical pressure time history with analysis window (a) and analysis window overlaid on chamber pressure measurement and RMS OASPL time history (b) and a one third octave plot for the test data compared to the scaled data (c).
ASMAT VALIDATION OF CFD
(COMPARISONS OF FREQUENCY WITHIN DUCT)

- Simulations of 5% scale rocket to model transient startup of motor
- Validated pressure temporal/spectral accuracy of CFD vs test data.
- Simulations showed good correlation with test data.
  - Matched pressure content above deck to 1000-1500 Hz
  - Matched pressure content below deck to 2000-3000 Hz
- Provided rationale and confidence to use CFD to predict environments for full-scale vehicles (up to ~150 Hz)
Solution: Implement hybrid approach of CFD + Computational Aero Acoustics (CAA) for liftoff acoustic fields

- Use high-fidelity CFD modeling to capture important plume physics (multi-phase plume, plume mixing and impingement, gas-water phase effects from deluge, etc.)
- Capture acoustic sources originating from plumes, impingement, capture water suppression effects
- Propagate using CAA from acoustic source surfaces enclosing noise source regions

Which CAA method is best suited for this application?

- CAA acoustic field propagation method must be able to resolve reflections, refraction and attenuation from interaction with structures such as launch platform and tower
- Two approaches under evaluation:
  - Boundary Element Method (BEM)
  - Farfield high-order Euler solution

Challenge: Identification of the Acoustic Source Regions

- Major challenge arises in defining envelope of source regions for handover from CFD to CAA
- Plume boundary shape is quite complex due to interaction with launch pad
- Example: Visualization of Noise Source regions for ASMAT Plume Impingement
SUMMARY

- The Fluid Dynamics Branch at MSFC has the mission is to support NASA and other customers with discipline expertise to enable successful accomplishment of program/project goals.
- The branch is responsible for all aspects of the discipline of fluid dynamics, analysis and testing, applied to propulsion or propulsion-induced loads and environments, which includes the propellant delivery system, combustion devices, coupled systems, and launch and separation events.
- ER42 supports projects from design through development, and into anomaly and failure investigations.
- ER42 is committed to continually improving the state-of-its-practice to provide accurate, effective, and timely fluid dynamics assessments and in extending the state-of-the-art of the discipline.