Fluid Dynamics and Propulsion at Marshall Space Flight Center

Marshall Technology Exposition

U.S. Space and Rocket Center

Davidson Center for Space Exploration

October 27, 2014

PROPULSION SYSTEMS DEPARTMENT

- **ER01** Propulsion Systems Department
  - **ER02** Resources Management Office
  - **ER20** Propulsion Systems Design & Integ. Division
    - **ER21** Engine Systems Branch
    - **ER22** Main Propulsion System Branch
    - **ER23** Spacecraft & Auxilliary Propulsion Systems Branch
    - **ER24** Propulsion Research and Technology Branch
  - **ER30** Propulsion Component Design & Devel. Division
    - **ER31** Turbomachinery Design & Development Branch
    - **ER32** Combustion Devices Design & Devel. Branch
    - **ER33** Valve, Actuators, & Ducts Design and Devel Branch
    - **ER34** Propulsion Detailed Design Branch
    - **ER35** TVC Systems Integration & Components Branch
  - **ER40** Structures, Thermal, and Fluids Division
    - **ER41** Structural & Dynamics Analysis Branch
    - **ER42** Fluid Dynamics Branch
    - **ER43** Thermal Analysis Branch
  - **ER50** Solid Propulsion Systems Division
    - **ER51** Solid Launch Systems & Analysis Branch
    - **ER52** Solid Separation & Manufacturing Systems Branch

FLUID DYNAMICS BRANCH STRUCTURE

Fluid Dynamics Branch

Branch Chief – Lisa Griffin
Assistant Branch Chief – Tom Nesman
Technical Assistant – Denise Chaffee
Technical Assistant - Kevin Tucker
Computer System Administrator – Dennis Goode

Computational Fluid Dynamics
Team Leader: Jeff West

Unsteady Flow Environments
Team Leader: Tom Zoladz

Acoustics and Stability
Team Leader: Jeremy Kenny

ER42 is comprised of three teams with a total of approximately 50 employees

FLUID DYNAMICS BRANCH APPLICATIONS

The Fluid Dynamics Branch (ER42) is a discipline centric branch responsible for all aspects of the discipline of fluid dynamics applied to propulsion and propulsion-induced loads and environments.

- ER42 work begins with design trades and parametric studies and continues through hardware development and flight.
- Project support also includes risk assessment, anomaly investigation and resolution, and failure investigation.

Main Propulsion System

- Tank Dynamics
- Cryofluid Management
- Feedline Flow Dynamics
- Valve Flow and Dynamics

Turbopumps

- Pump Dynamics
- Turbine Dynamics

Liquid Combustion Devices

- Injection Dynamics
- Chamber Acoustics
- Combustion Stability
- Nozzle Dynamics

Solid Rocket Motors

- Motor Dynamics
- Nozzle Dynamics
- Combustion Stability

Coupled Systems

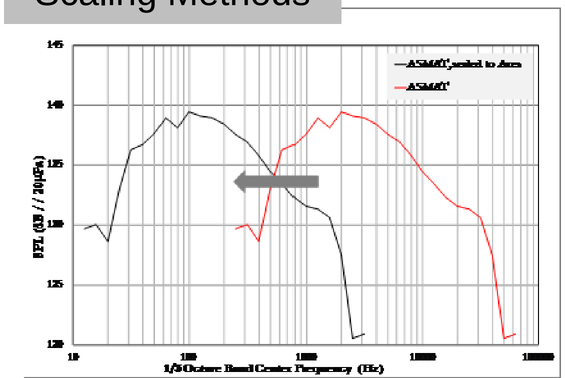
- Feed System Dynamics
- Coupled Pump/MPS Dynamics, e,g,, Pogo
- Thrust Oscillations and its Impact on the Vehicle
- Tank Slosh and its Impact on Vehicle Stability and GN&C

Launch, Separation, and Plume-Induced Environments and Debris

- Liftoff Acoustics
- Separation Acoustics
- Overpressure
- Inflight Plume Generated Noise
- Noise Mitigation
- Hydrogen Entrapment
- Liftoff Debris Transport

FLUID DYNAMICS ANALYSIS

Scaling Methods

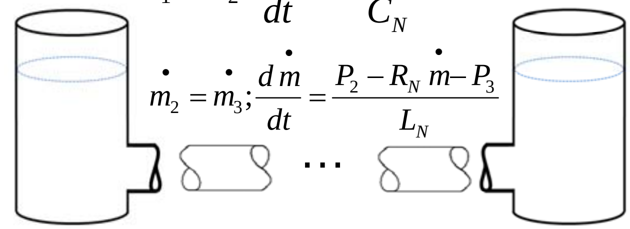


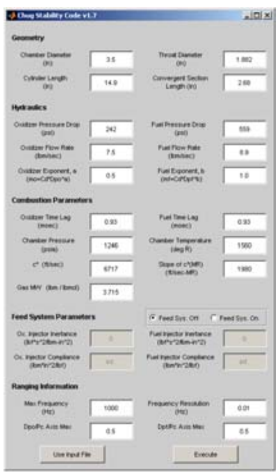
ER42 conducts all levels of fluid dynamics analysis from scaling methods through 3D Unsteady CFD

Lump Parameter Modeling

$$P_1 = P_2; \frac{dP}{dt} = \frac{\dot{m}_1 - \dot{m}_2}{C_N}$$

$$\dot{m}_2 = \dot{m}_3; \frac{d\dot{m}}{dt} = \frac{P_2 - R_N \dot{m} - P_3}{L_N}$$



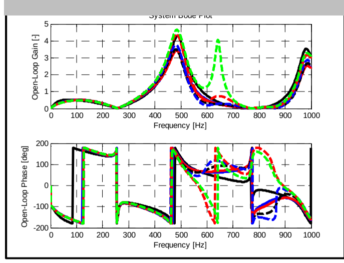


$$x(\omega) = \frac{\bar{X}\sin\left(\omega(\bar{\tau}_{T,o} - \bar{\tau}_{T,f})\right)}{\sin(\omega\bar{\tau}_{T,f}) + \theta_g \omega \cos(\omega\bar{\tau}_{T,f})}$$

$$y(\omega) = \omega$$

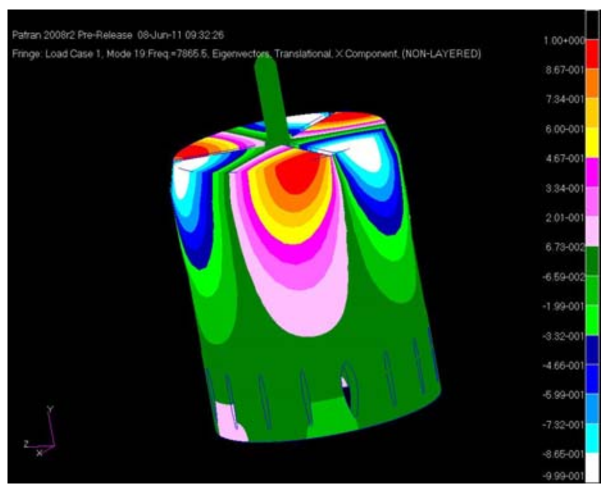
$$z(\omega) = \frac{\bar{F}\sin\left(\omega(\bar{\tau}_{T,f} - \bar{\tau}_{T,o})\right)}{\sin(\omega\bar{\tau}_{T,o}) + \theta_g \omega \cos(\omega\bar{\tau}_{T,o})}$$

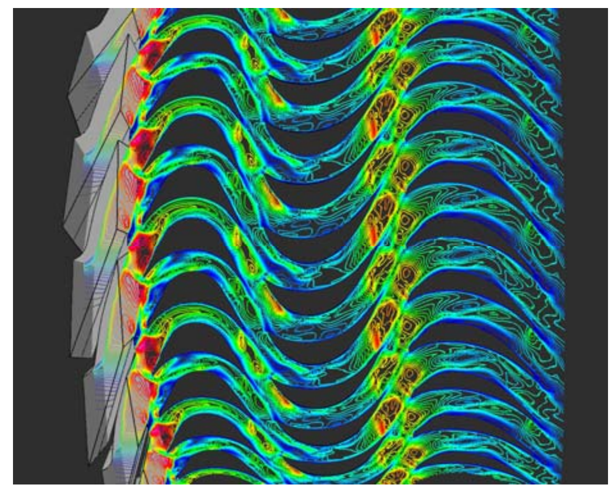
Gain / Phase Plots



System Stability Modeling

Finite Element Modeling



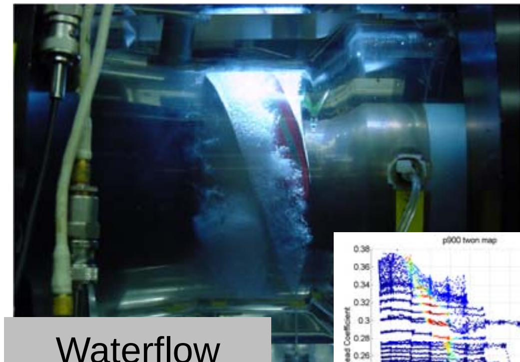
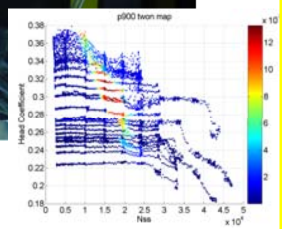


Computational Fluid Dynamics

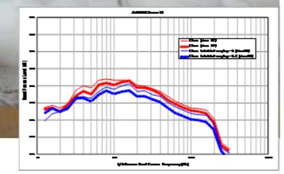
FLUID DYNAMICS TESTING

ER42 conducts and supports testing for hardware and technology development and verification, and analysis validation

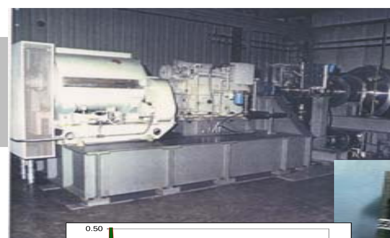
- Primary responsibility for cold flow and scale model acoustics tests
- Secondary responsibility for hot system and component testing

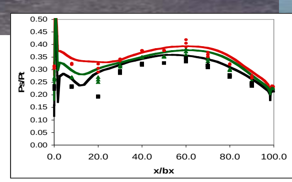



Waterflow Testing in Pump Facility

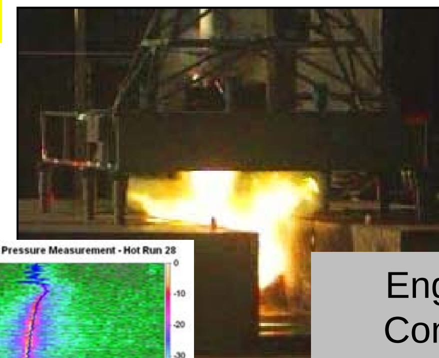
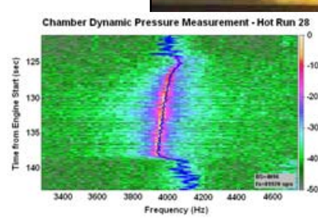



Scale Model Acoustics Testing

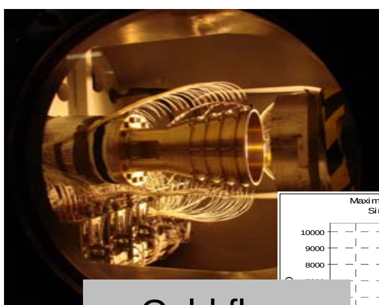
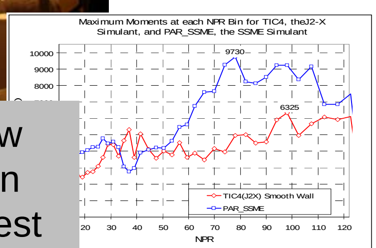




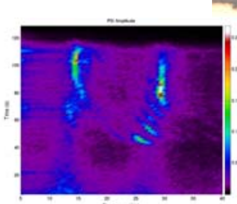
Airflow Testing in Turbine Facility

Engine and Component Testing

Cold flow testing in Nozzle Test Facility




Solid Rocket Testing

FLUID DYNAMICS BRANCH TECHNOLOGY

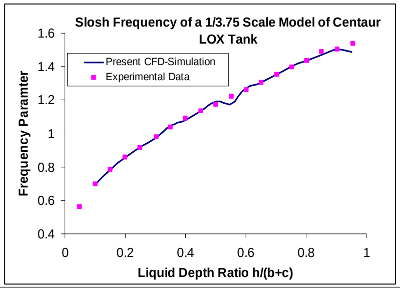
The Fluid Dynamics Branch is continually improving the state-of-the-practice for fluid dynamics support for propulsion system design & development

- **Why?**
  - To enable development of robust propulsion hardware that fully meets design requirements
  - To facilitate reductions in the cost of access to space by—
    - Lowering design and development costs
    - Lowering production costs (via evaluation of fluid dynamic impacts of advanced manufacturing techniques)
- **How?**
  - Increasing tool/test fidelity via appropriate technology pull from the state-of-the-art
    - Across the entire spectrum of fluid dynamics analysis
    - Tests-cold flow/hot fire, subscale/full scale
    - Test and flight data acquisition capabilities
  - Validation of new capabilities
  - Integration of validated, high-fidelity capabilities into fluid dynamic support for programs
- **By what means?**
  - Strategic partnerships with small business and universities
  - Active participation in the NASA SBIR/STTR program
  - Internal funding from projects and technology opportunities (e.g. CIF, TIP, Tech Excellence, etc.)

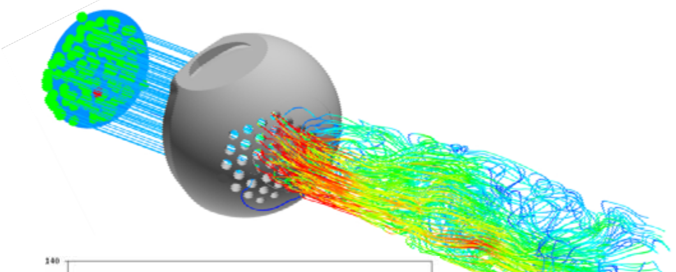
Main Propulsion System (MPS) design & development support encompasses:

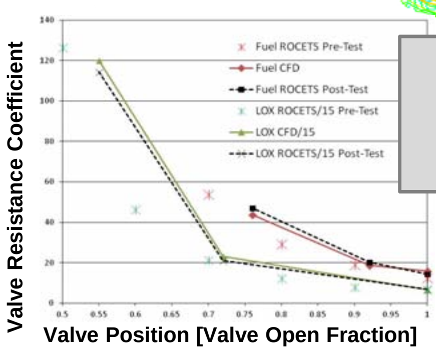
- **Tanks (including internal components)**
  - ✓ Propellant Tank Slosh
  - ✓ Pressurization
  - ✓ Drain
- **Valves**
  - ✓ Flow Patterns & Mean Pressure Drop
  - ✓ Unsteady & Transient Fluid Environments
- **Feedlines (including internal components)**
  - ✓ Pressure Drop and Flow Uniformity
  - ✓ Unsteady Pressure Environments

Earth to Orbit Tank Simulation

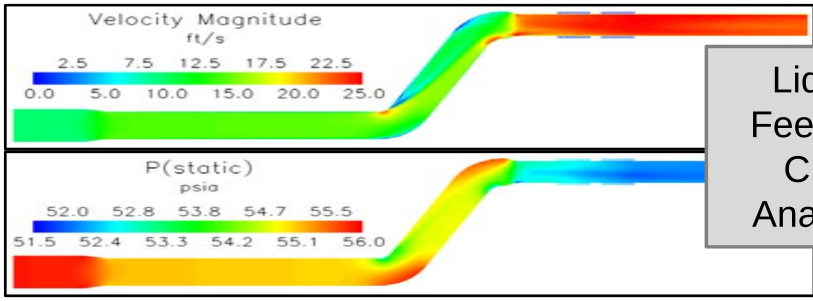


Improvement to Classic Mass-Spring Model

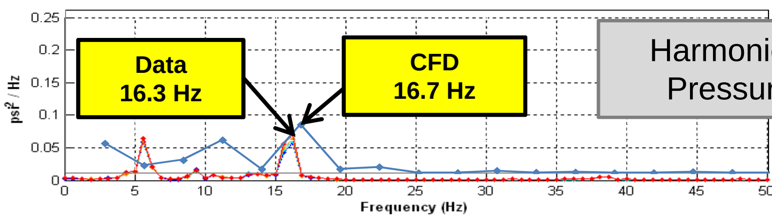




Partially Open Ball Valve Simulation



Liquid Feedline CFD Analysis



Harmonic Analysis of Pressure Tap Data

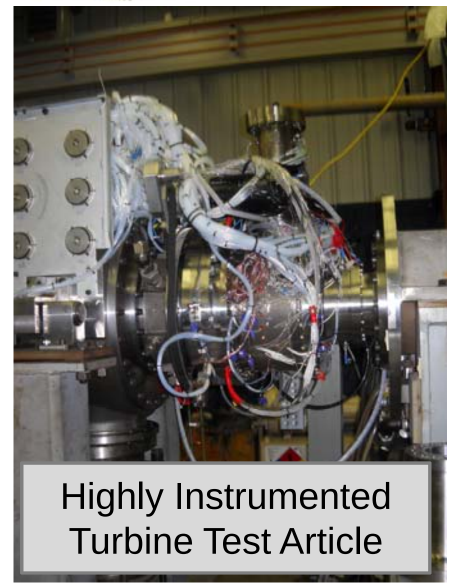
TURBOPUMPS
Turbines

Turbine Unsteady CFD Analysis

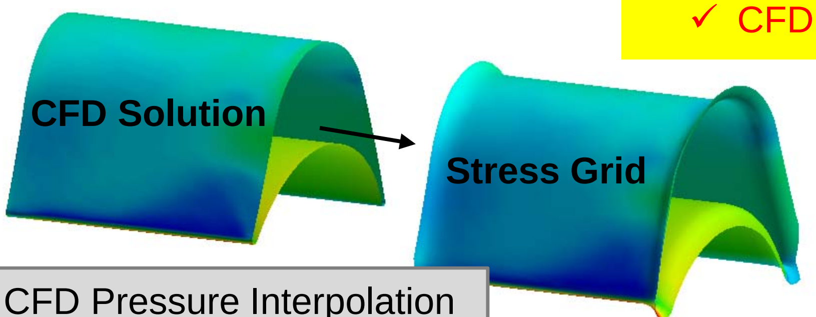
Turbine design & development support includes:

- **High-fidelity, unsteady, 3D, full 360° turbine CFD simulations**
  - ✓ Quick turnaround design parametrics
  - ✓ All flow features impacting fluid forcing functions are modeled
  - ✓ Unsteady pressure histories delivered in temporal or frequency domains
- **Airflow testing of highly instrumented turbine models in scaled air conditions**
  - ✓ Steady & unsteady pressure loadings
  - ✓ Interstage cavity pressures
  - ✓ Wide range performance mapping
  - ✓ CFD validation

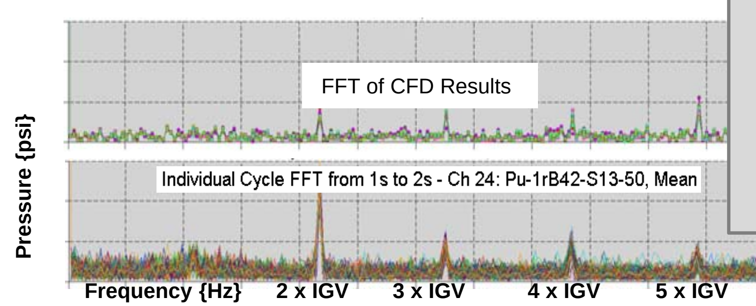
Turbine Airflow Rotating Assembly



Highly Instrumented Turbine Test Article



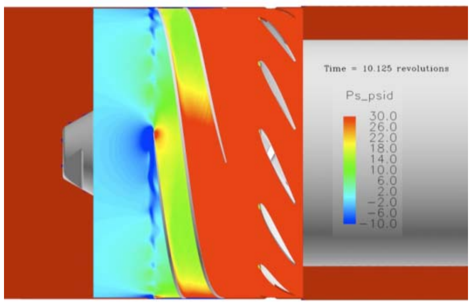
CFD Pressure Interpolation onto Stress Grid



Harmonic Analysis of Pressure Data

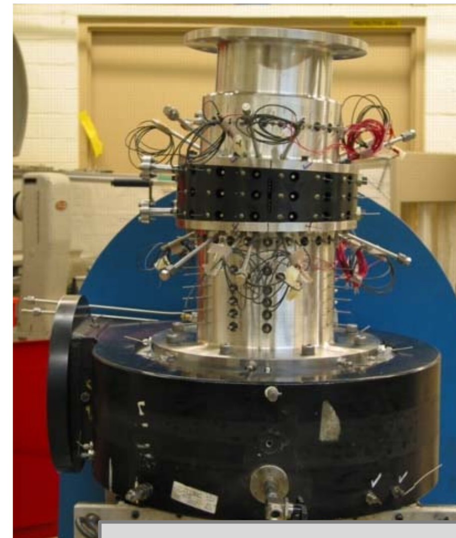
TURBOPUMPS
Pumps

Pump Unsteady CFD Analysis

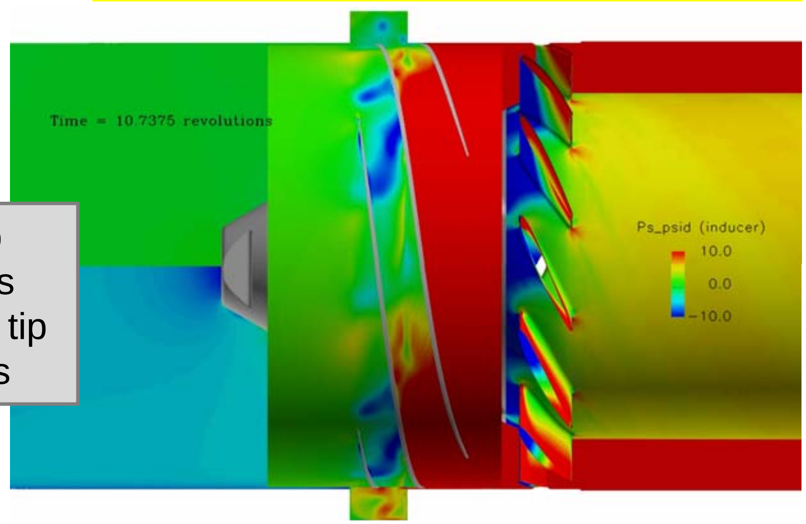


Pump design & development support includes:

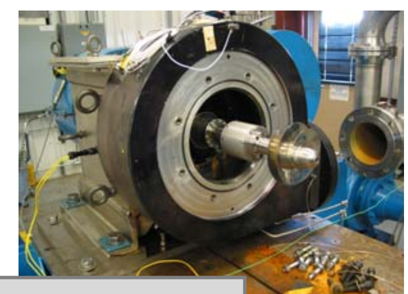
- **Comprehensive steady & unsteady pump evaluations**
  - ✓ Done at scaled engine conditions via dense instrumentation suites
  - ✓ Cavitation trend identification
  - ✓ High speed flow visualization
- **High-fidelity CFD simulations**
  - ✓ Time accurate CFD simulations provide insight into cavitation
  - ✓ Used to identify critical unsteady flow interactions between inducer blades and cavitation suppression grooves



Pump with upstream MPS element



Unsteady pump CFD simulations capture inducer tip vortex dynamics

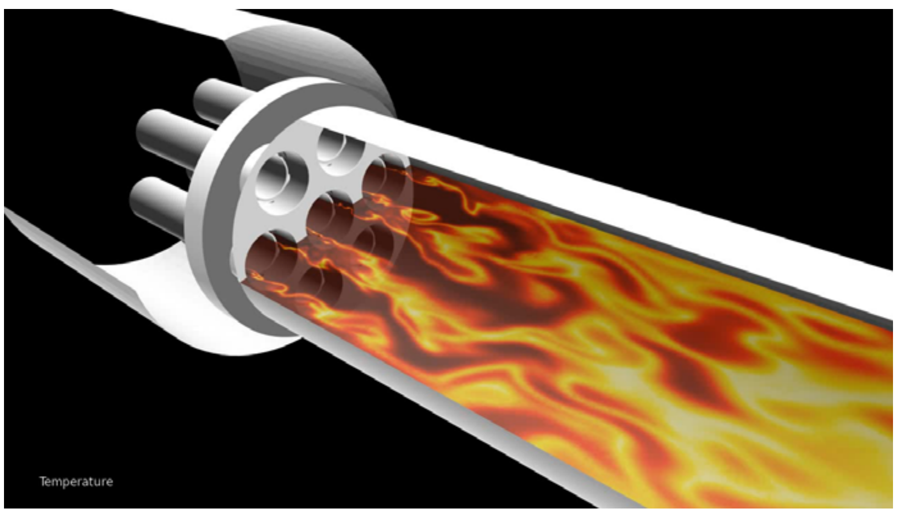


2-blade inducer with on-rotor dynamic force measurement system

Injectors and Combustion Chambers

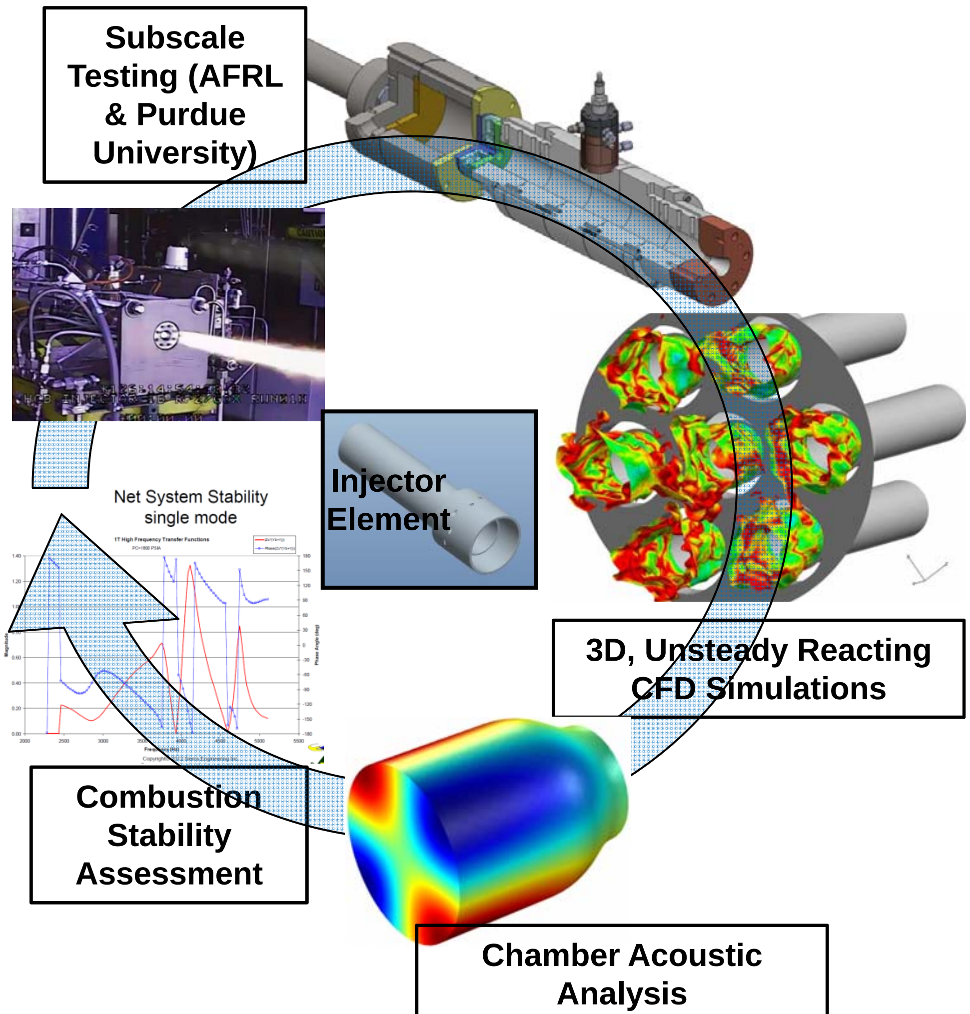
Branch responsibility in support of liquid rocket engine injector/chamber design & development

- Large and small engines
- Design, analysis & test support
  - ✓ Performance
  - ✓ Pressure, acoustic & thermal environments
  - ✓ ***Combustion stability—current emphasis***



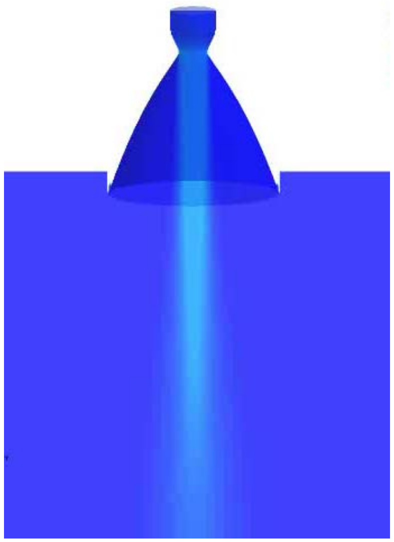
Reacting flowfield from a 7-element CFD injector simulation

Injector Design & Combustion Stability Assessment Process



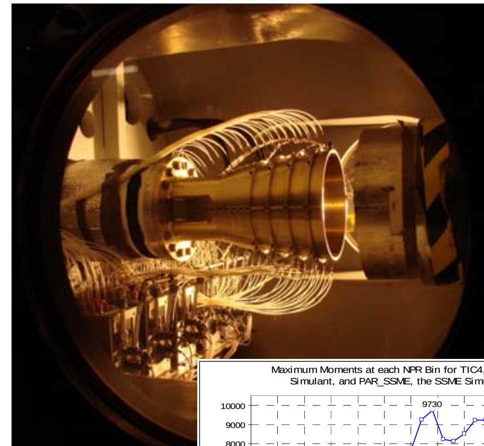
COMBUSTION DEVICES
Nozzles

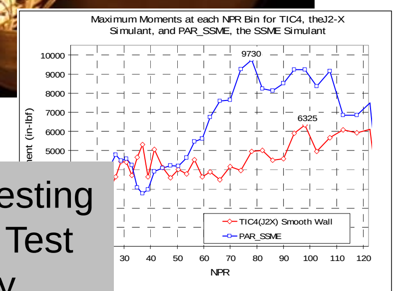
Upper stage engine transients (with stub nozzle)



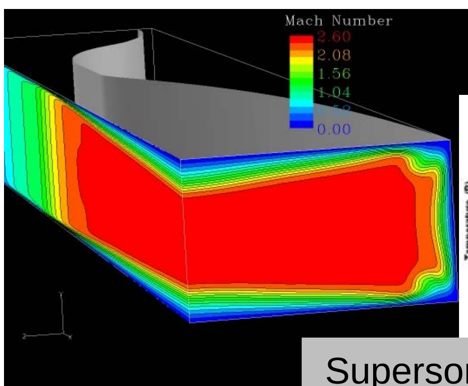
Nozzle design & development support includes:

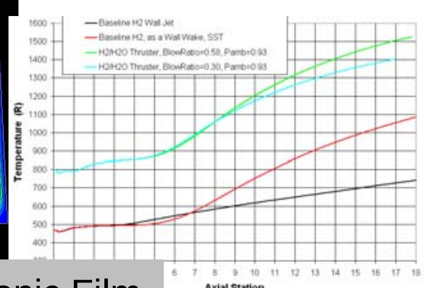
- **High-fidelity, unsteady, 3D, full 360^{o} CFD simulations**
  - ✓ Performance
  - ✓ Transient side loads
  - ✓ Film Cooling
- **Airflow testing of highly instrumented nozzles in scaled air conditions**
  - ✓ Pressure loads & performance
  - ✓ Heat transfer
  - ✓ Evaluation of advanced nozzle concepts—dual bell, aerospike, expansion-deflection, etc.
  - ✓ Data for CFD validation



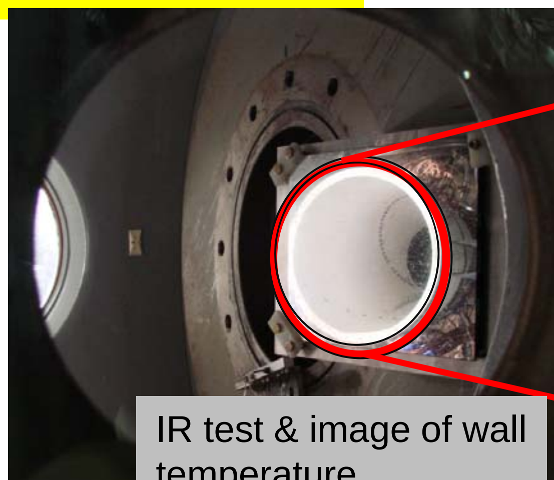


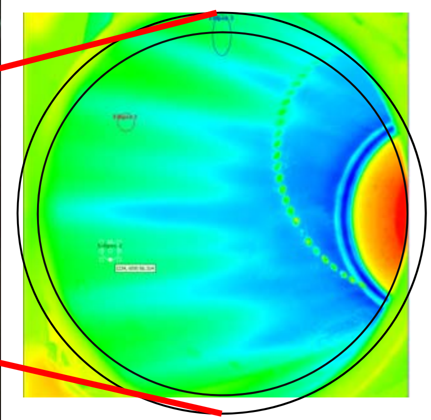
Cold flow testing in Nozzle Test Facility





Supersonic Film Cooling

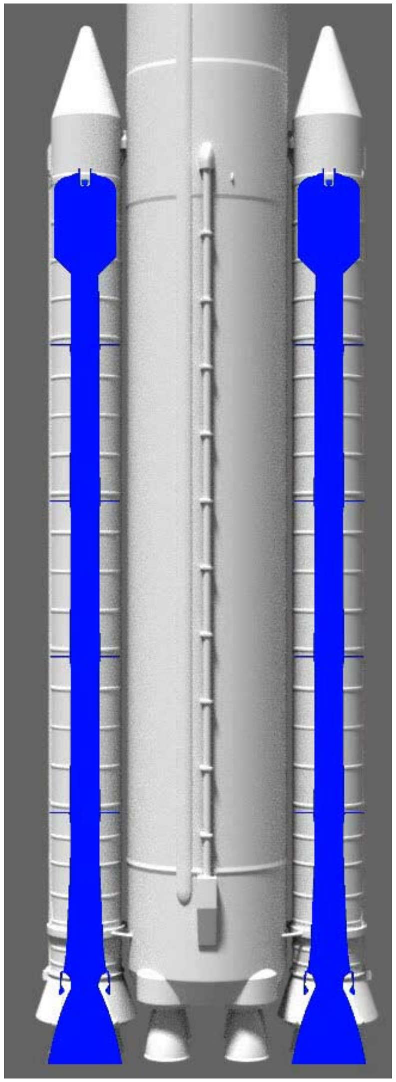




IR test & image of wall temperature

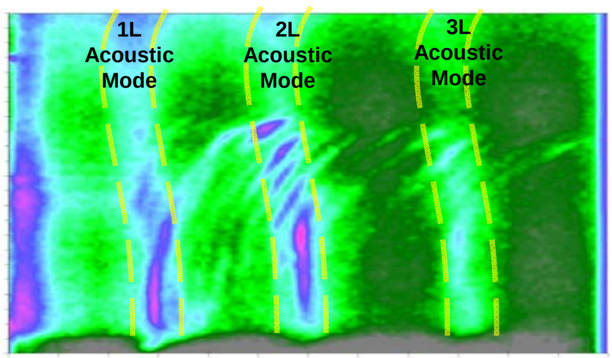
SOLID ROCKET MOTORS

CFD simulation of booster start transient

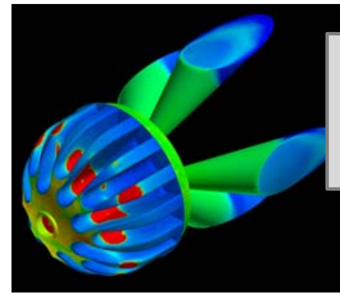


Solid rocket motor design & development support includes:

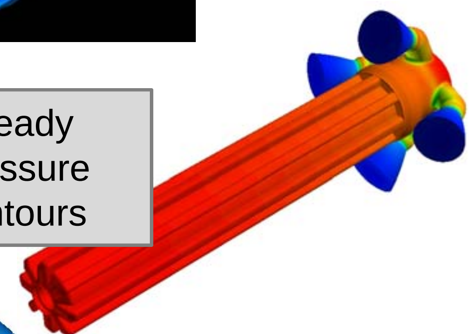
- Large booster-class motors
- Small motors-ullage settling, booster separation & launch abort
  - ✓ Performance
  - ✓ Environments-pressure, acoustic & thermal
  - ✓ Stability



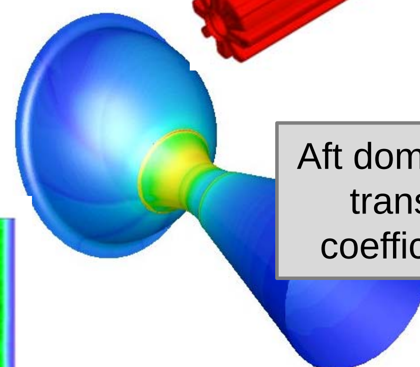
Hot Fire Test Oscillatory Pressure Characteristics



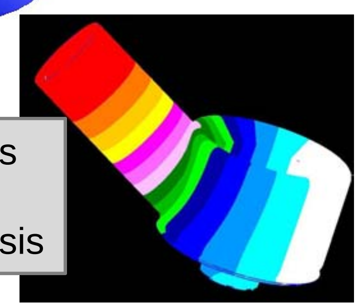
Temperature contours during ignition



Steady Pressure contours



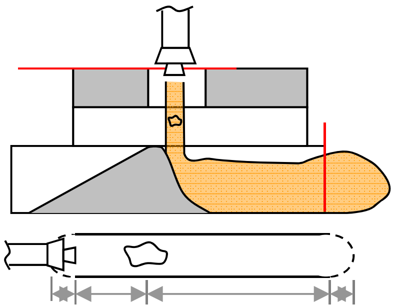
Aft dome heat transfer coefficients



Mode shapes from finite element analysis

LAUNCH ENVIRONMENTS

1D Linearized Physics Models

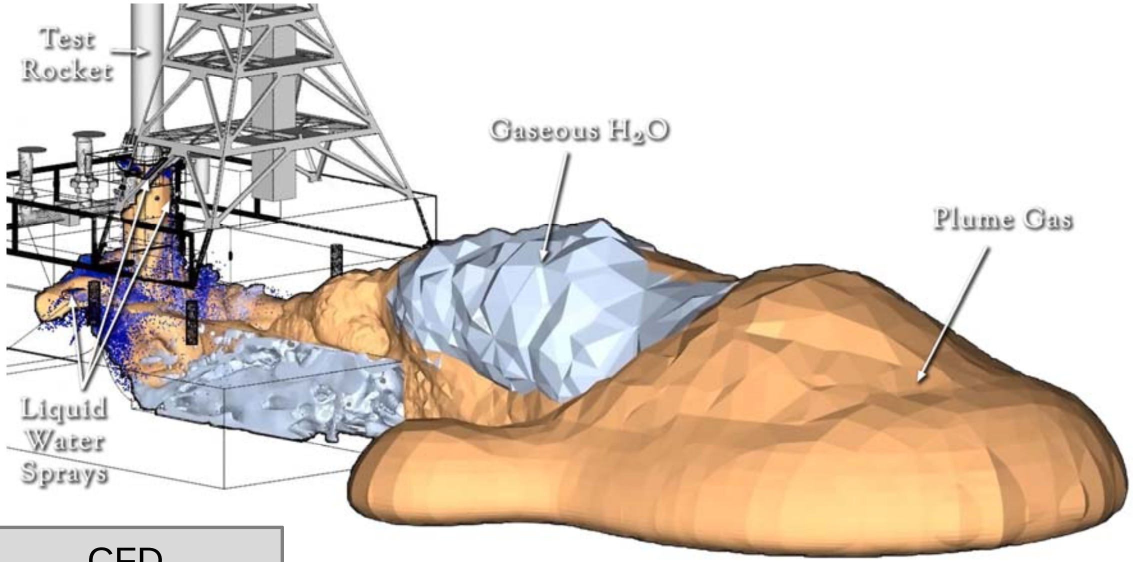


ER42 Develops the Fluid and Acoustic Environments for Launch

- ✓ Liftoff Acoustics
- ✓ Overpressure
- ✓ Sound Suppression
- ✓ Liftoff Debris Transport
- ✓ Hydrogen Entrapment

Multiple Levels of Analysis and Testing Used to Accomplish this Work

Flight Tests

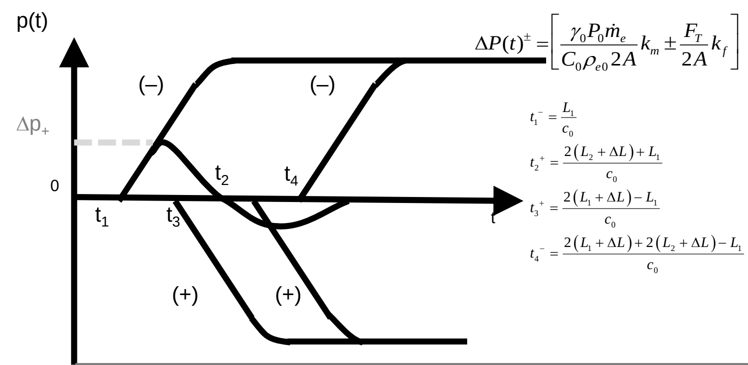


CFD

Scale Model Tests

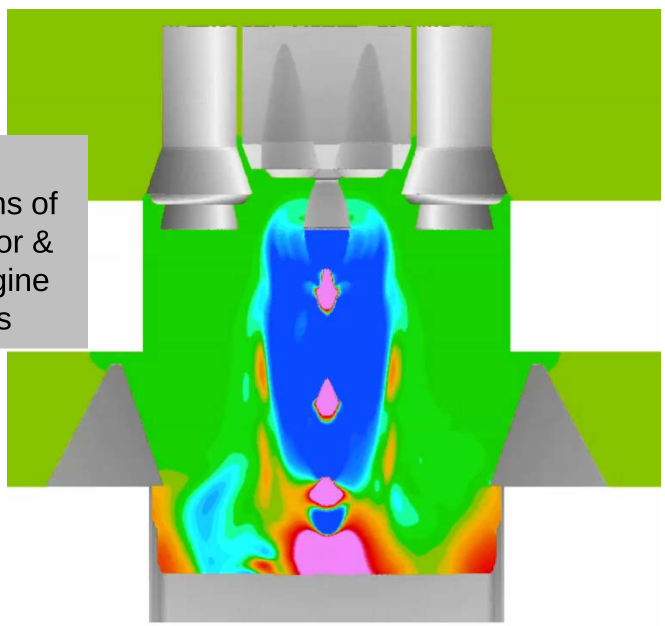
Overpressure Predictions

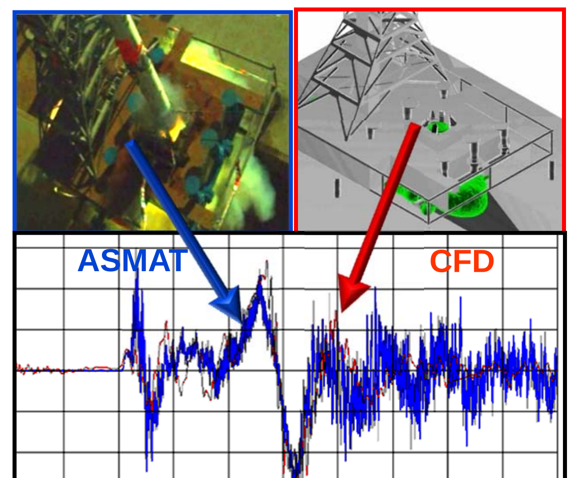
- **Made by use of a combination of analytical models, CFD simulations and test/flight data**
- **CFD has recently shown to represent overpressure very accurately without the inclusion of water**
  - ✓ Demonstrated ability to capture IOP and DOP waves at several locations for dry tests
  - ✓ Addresses limitations of analytical models
  - ✓ Accounts for complex flow scenarios and three-dimensional launch pad geometry
  - ✓ Provides understanding where unknowns exist



4-Wave Physics Model

CFD simulations of solid motor & liquid engine plumes



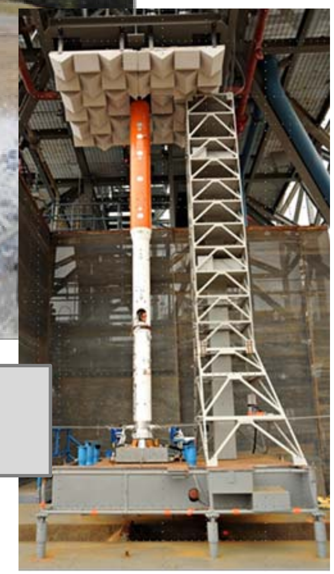


Comparisons of CFD predictions with ASMAT data

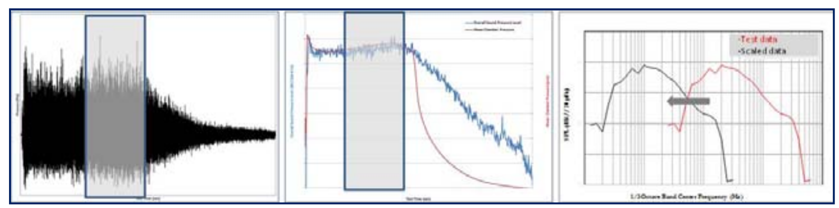
LAUNCH ENVIRONMENTS
Liftoff Acoustics

Liftoff Acoustics

- Liftoff noise is generated by rocket exhaust mixing with surrounding atmosphere & its interactions with surrounding launch structures
- ER42 Liftoff Environment Definition Process
  - ✓ Initial liftoff acoustic environment derived from previous/historical flight test data
  - ✓ Acoustic scale model designed and tested to validate liftoff acoustic environments and water sound suppression system design.



Scaled Model Acoustic Testing at MSFC



Typical pressure time history with

- Analysis window (a)
- Analysis window overlaid on chamber pressure measurement and RMS OASPL time history (b)
- A one third octave plot for the test data compared to the scaled data (c).

SUMMARY

- The Fluid Dynamics Branch at MSFC has the mission 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