Hybrid Computational Fluid Dynamics And Computational Aero-Acoustic Modeling For Liftoff Acoustic Predictions

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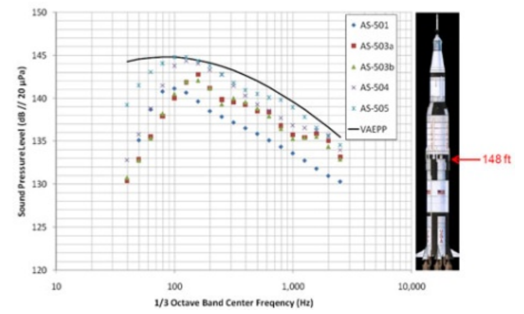
Outline

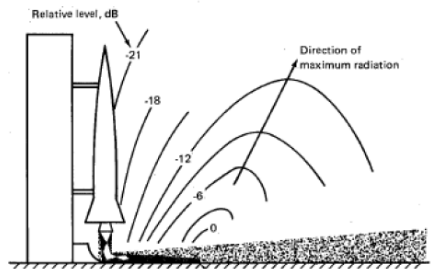
- NASA Liftoff Environment Analysis
- Traditional Engineering Methods and Important Role of CFD
- MSFC Liftoff CFD Capabilities
- Samples of Loci/CHEM capabilities
- Approach to Couple CFD with CAA for liftoff environment
- Rationale for Selection of BEM based CAA
- Implementation Roadmap and Goals
- Conclusions

MSFC Liftoff Acoustics Analysis Activities

- MSFC Fluid Dynamics Branch responsible for NASA liftoff environments
- Standard approach for acoustic environment prediction: Apply empirical plume noise methods (VAEPP, SP-8072, …)
- Resort to knock-down factors for effects not captured in empirical methods
- Launch pad topology uncertainties
  - Sound reflections from complex pad geometry
  - Plume impingement on launch platform
  - Typically summed up as + 6 dB scale-up factor
- Water deluge sound suppression effects
  - Would result in knock down factor
  - Currently not used since no historical database available for credible bounds
- Mature, validated CFD capability in place for liftoff flow field analysis
- Can we employ CFD to capture lift-off acoustic phenomena not captured by engineering methods?



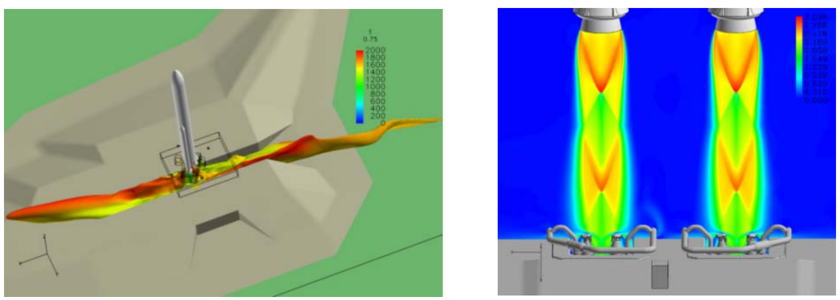
VAEPP



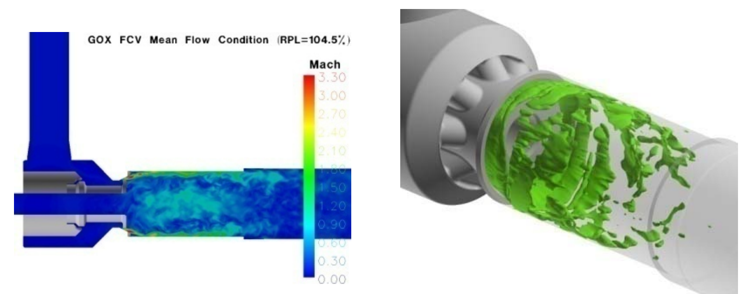
SP-8072

MSFC CFD Analysis Activities

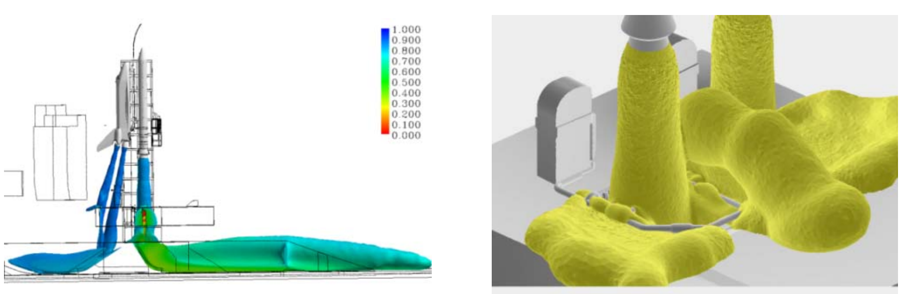
- CFD analysis tool at MSFC is Loci/CHEM
- MSFC CFD analysis supports:
  - Propulsion systems: Propellant delivery unsteady flows, combustion instability
  - Liftoff plume induced environments: Mobile launcher, launch pad, and flame trench plume flow environments
  - Ignition Over-Pressure (IOP) and start-up plume transient environment
  - Plume and wind driven liftoff debris transport
  - Launch pad hydrogen entrapment



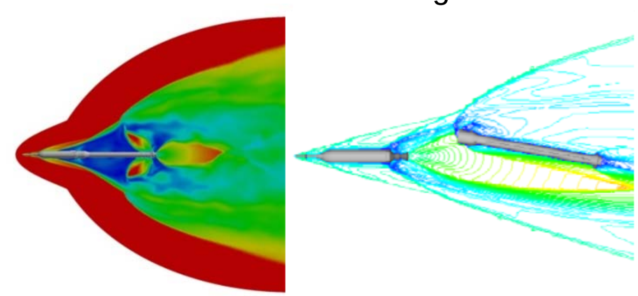
Launch Pad And Flame Trench Environment



Hybrid RANS/LES Flow Control Valve
100kHz Acoustic Driven Fatigue Failure



Space Shuttle, Ares, SLS liftoff plume flow



Ares I staging IOP
(Moving body + plume transient flow)

Loci/CHEM CFD Framework

- **Loci** computational framework
  - Highly scalable automatic parallelization platform for computational field simulations
  - Developed at Mississippi State University by Dr. Ed Luke
  - Open Source under the Lesser GNU Public License (LGPL) License.
- **Loci/CHEM** density-based Navier-Stokes solver implemented in the Loci framework
  - Generalized unstructured grids
  - RANS, URANS, DES, Hybrid RANS/LES turbulence modeling
  - Eulerian multiphase models for particulates and droplets
  - Lagrangian multiphase models for particulates and droplets with particle vaporization, condensation, combustion
  - Real fluids EOS for cryogenic injection and combustion analysis
  - Non-gray radiation transport models (particle and gas phase radiation)
  - Solution adaptive mesh refinement with various error estimators available
  - Mesh deformation for fluid-structure deformation and fuel burn-back surface
  - Overset moving body with prescribed motion and 6-DOF
  - Body Collision 6-DOF modeling
- Extensively verified using Method of Manufactured Solutions Technique
- 2^{nd} order space and 2^{nd} order time accurate, but not low dispersion/low dissipation
- Production simulations typically 10M to 300M cells on 3000+ processors

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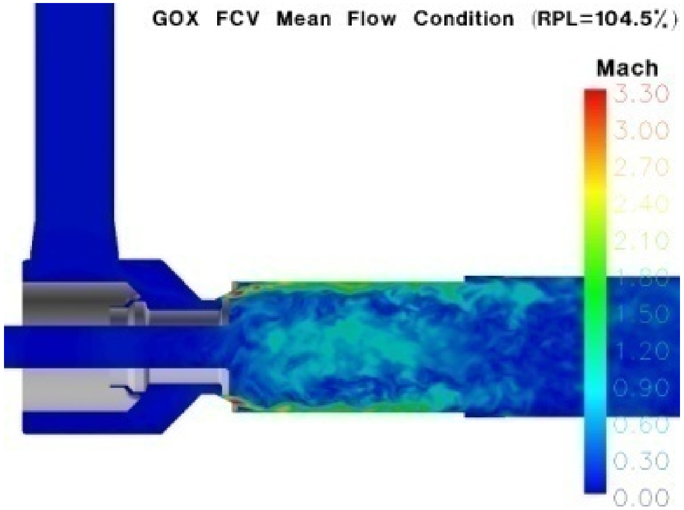
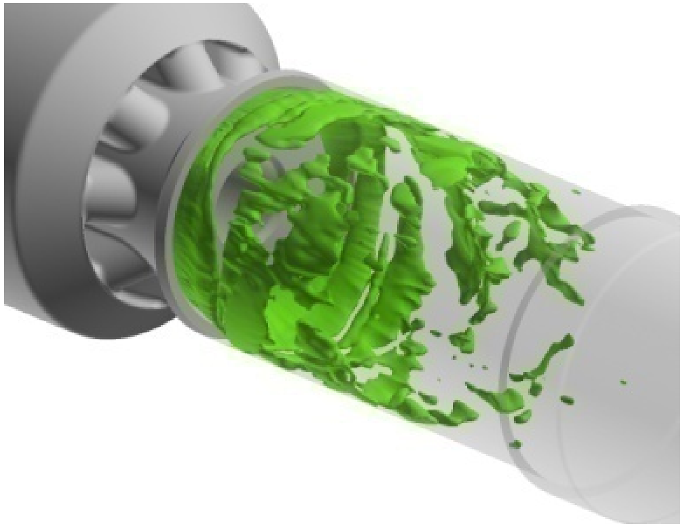
Samples of MSFC CFD Capabilities

- Acoustic driven loads
  - SSME flow control valve fatigue fracture due to acoustic loading
- Engine start-up transients and Ignition Overpressure
  - Ares-I Scale Model Acoustic Test (ASMAT)
- Water injection for launch pad water deluge simulation
  - Two phase flow simulation with water droplet injection
  - Effects of water phase on plume acoustic sources on pad
- Vehicle liftoff transient flow effects on pad and flame trench environment
  - Full liftoff simulations staring from engine flow start-up transients all the way through liftoff trajectory vehicle motion

CFD for Internal Acoustics

- Application in capturing internal flow acoustics
- Space Shuttle fuel flow control valve supersonic flow and impingement
- Exciting tangential and radial mode cavity acoustics
- Valve poppet developed crack due to high cycle fatigue
- Loci/CHEM Hybrid RANS/LES simulations
- Captured occurrence of various tangential and radial modes up to 100kHz
- Excellent correlation with FEM modal analysis and failure mode forensic analysis
- Validated against calibration rig tests





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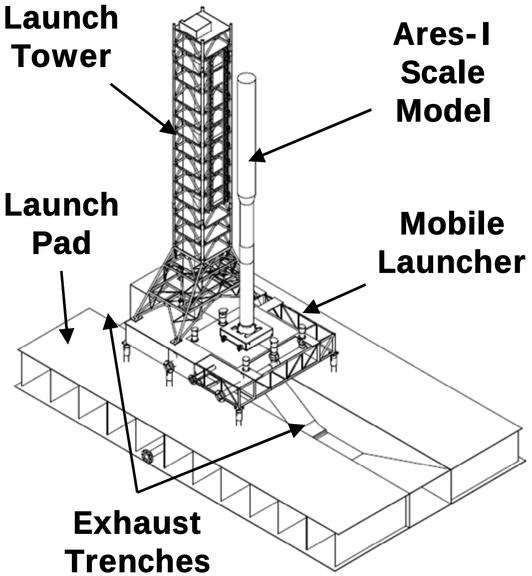
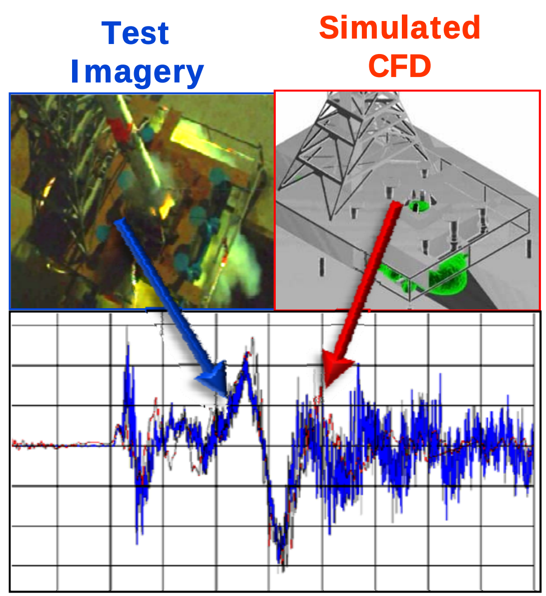
ASMAT IOP Simulation

- Ares-I Scale Model Acoustic Test (ASMAT)
  - Tests of 5% scale model of Ares I vehicle
  - Address vibration and acoustic risks from Constellation Program.
  - Scale model powered by Rocket Assisted Take-Off (RATO) motor
  - Stationary during firing
  - 100+ pressure transducers on launch structure and vehicle
  - Tests performed with and without water deluge

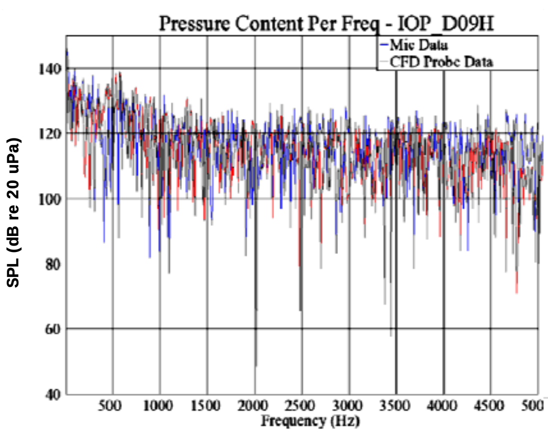


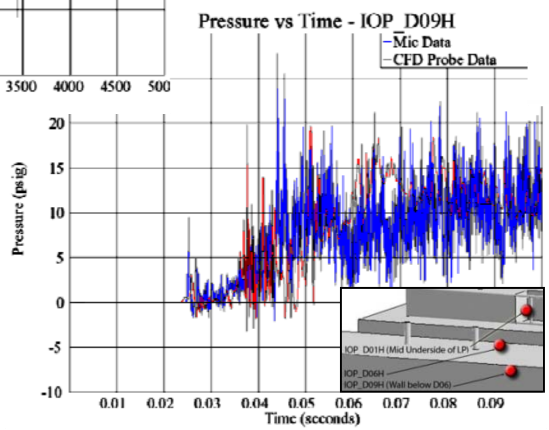
- Simulation Interest
  - Demonstration of CFD capability for IOP prediction
  - Well documented set of high fidelity measurements suitable for CFD validation
  - Compare flow features to available imagery (Visible, IR cameras)

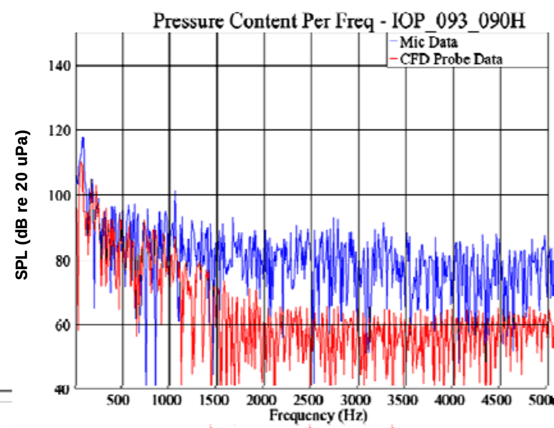


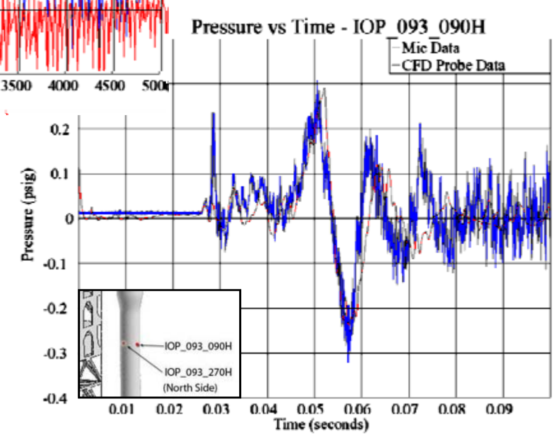
ASMAT Nearfield and Farfield Acoustics

- Quantitative comparison of time and freq domain signals
- Major pressure peak amplitudes and timings captured with 5-10% error
- Nearfield (sensor close to source) frequency content captured well
- Farfield frequency content lost above ~1000 Hz
- Launch vehicle acoustic frequencies must be resolved to 5kHz minimum
- Requires improved grid resolution and algorithms for acoustic content tracking or separate CAA acoustic field propagation approach









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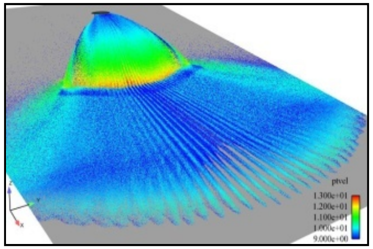
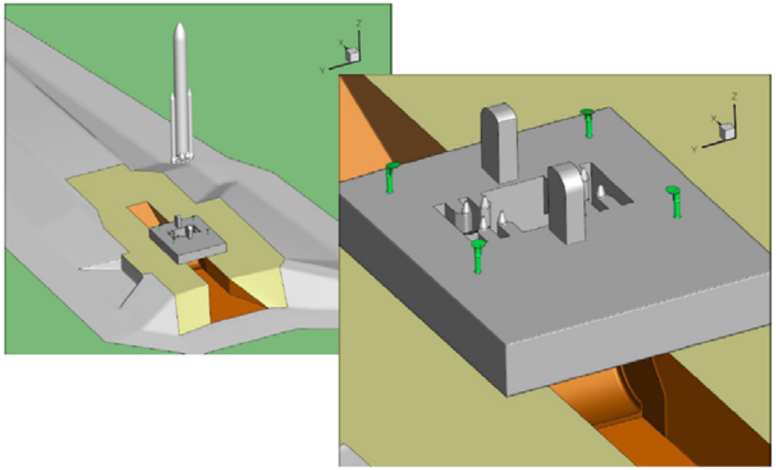
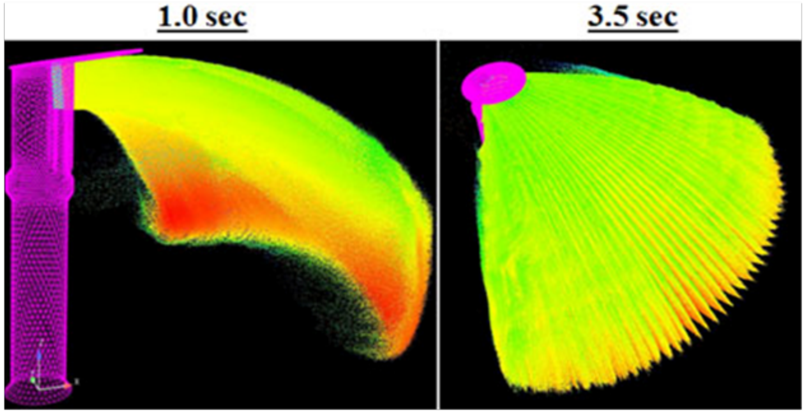
Launch Pad Water Deluge Effects

- Pathfinder simulations of water injection into launch pad plume environment for SLS concepts
- LC39 launch pad with detailed flame trench
- Launch pad with four rainbirds emitting sprays of water – uneducated guess on placement
- Mixing of liquid engine and SRB plume composite gas mixtures
- Lagrangian particle model in Loci/CHEM used to model the water spray with water drop break-up and phase change
- Approx. 200M cells, Tracking Tens of millions of particles







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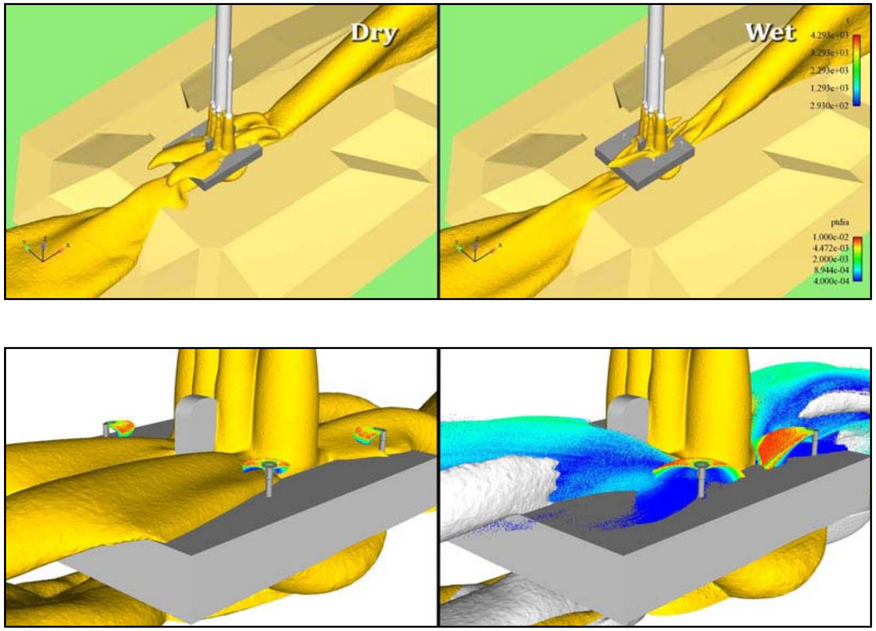
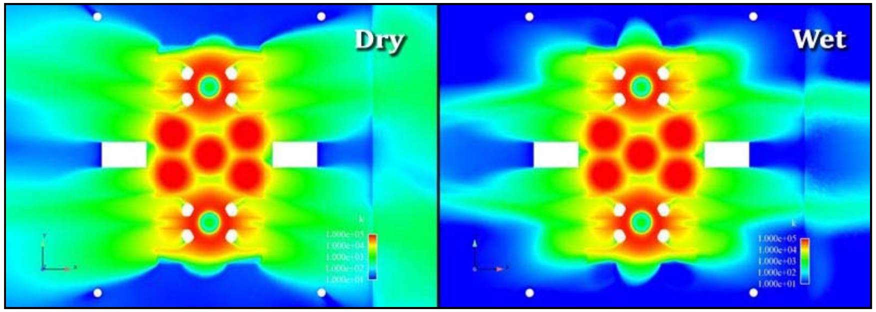
Launch Pad Water Deluge Effects

- Presence of water on deck surface considerably changes turbulent kinetic energy regions from plume spillage
- Alters impedance for plume mach wave noise reflection
- Pathfinder CFD simulations demonstrated possibility of multi-species, multi-plume liftoff simulations with multi-phase gas-water effects
- Practical design application: Use CFD modeling to target regions of high turbulent kinetic energy to reduce noise sources
- Support launch pad design with targeted placement of rain birds for maximum acoustic mitigation effect
- Challenge will be to resolve acoustic wave propagation in direct simulation: hybrid CFD-CAA seems only reasonable approach



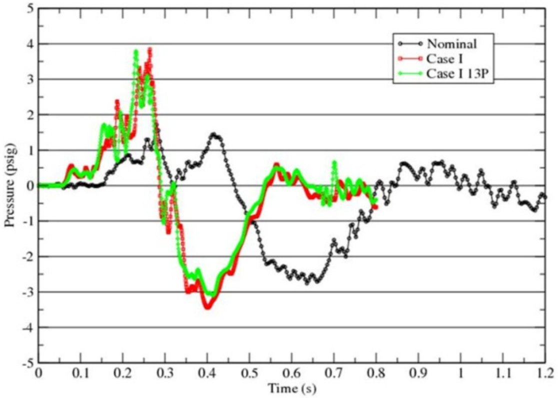
Reduction of Plume 500 K Iso-Surface from 0.7 to 4.5 seconds



Reduction of turbulent kinetic energy at deck level

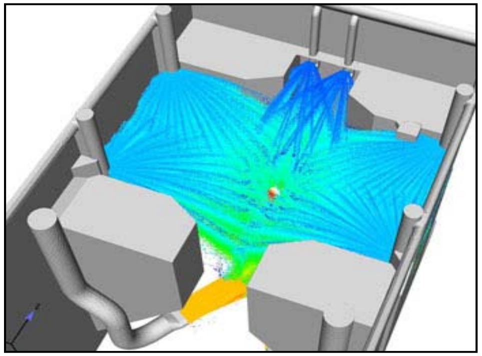
Flame Trench Water Deluge Effects

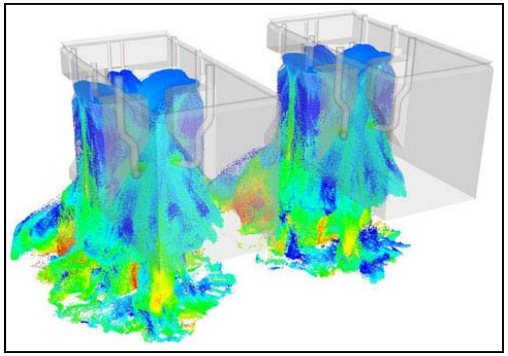
- Single-phase, gas-only CFD predicts incorrect (faster) trench wave development compared to experimental data
- Presence of liquid water reduces mixture sound speed, slowing wave propagation



'Nominal' is experimental data

- Achieving stable Loci/CHEM multi-phase CFD runs of Water Deluge
- Injecting water at 200,000 gallons per minute with 30M particles active in launch pad SRB holes





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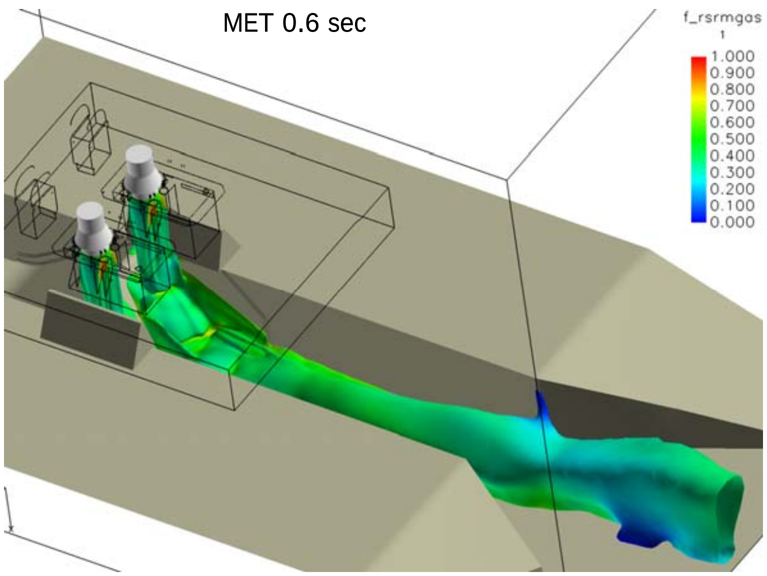
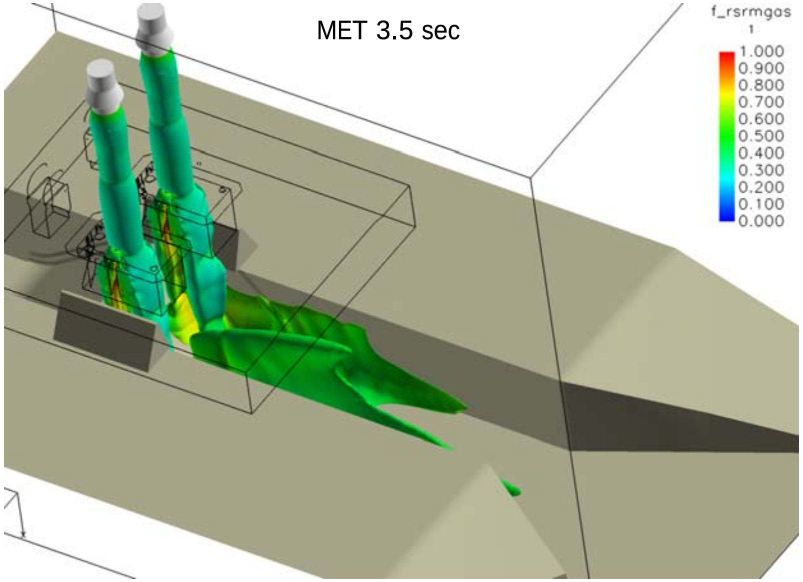
Shuttle Liftoff Plume Flow

- Space Shuttle SRB plume impingement environment
- Transient trench flow starting from SRB ignition followed by moving body plume transient plume impingement environment
- Captures transient start-up flow and IOP under launch pad and plume spillage onto pad deck during liftoff motion
- Overset grid 6-DoF simulation





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Extend CFD Analysis to Liftoff Acoustic

- Examples demonstrate Loci/CHEM CFD tool offers validated high-fidelity physics capability
- Mature CFD modeling capability is in place to capture many dominant liftoff aerothermal flow environment features
- Desired next step to apply this multi-physics capability to also tackle effects on launch acoustic environment
- Important to retain complex physics feature modeling capability since they also drive acoustic field characteristics
  - Multiple plumes with different plume gas composition (directivity)
  - Plume impingement, spillage turbulence modeling (new sources)
  - Turbulent plume mixing, requiring LES (Mach wave noise)
  - Plume characteristics under launch pad and in flame trench
  - Water deluge multi-phase effects on turbulent (acoustic) energy
- Problem: Loci/CHEM numerics are 2^{nd} order time, 2^{nd} order space accurate but not low dispersion/low dissipation
- May be too dissipative for preserving farfield acoustics (see ASMAT example)

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CFD Based Liftoff Acoustic Modeling

Two avenues towards high-fidelity CFD based liftoff acoustics predictions

- Long-term approach: Improve CFD algorithms beyond current 2^{nd} order accuracy
  - Higher order spatial and temporal accuracy
  - Lower numerical dissipation schemes
  - Difficult to achieve while retaining multi-species, reacting, turbulent plume flow important for capturing acoustic sources
  - Evaluating various higher order numerics developments (low dissipation schemes), but not production ready

- Near term approach: Implement hybrid approach of CFD + CAA
  - Utilize existing plume modeling fidelity to capture acoustic sources originating from plumes, impingement, water suppression effects
  - Existing CFD modeling features important physics (multi-phase plume, turbulence, LES, gas-water phase effects from deluge, etc.) but too dissipative
  - Propagate CAA from source surfaces enveloping noise source regions
  - Reduced risk and timely availability: Only requires development of communication between Loci/CHEM CFD results and existing CAA solutions

Computational Acoustic Simulation Approaches

Approach	Method Description	Prediction Quality	Computational Cost / Practical Feasibility
Direct CFD Method (without any Acoustic Solution Method)	Solve Full Navier-Stokes Equations - Direct Numerical Simulations (DNS) - Large-Eddy Simulations (LES, MILES) - Unsteady Reynolds Avg. NS (URANS)	Best Good but Questionable Poor	Most Expensive / Not feasible Expensive / Not Feasible Least Expensive / Unreliable
CFD-CAA Method - CFD-LEE - CFD-APE	Coupled Navier-Stokes (LES) and Linearized Euler Equation (LEE) or Acoustic Perturbation Equation (APE)	Good	Extremely Expensive Due to Mesh Resolution Requirements of Both LES and Acoustics Only Feasible for Small-Scale
CFD-Surface Integral Analytical Methods (Lighthill Kirchhoff or FWH)	Coupled Navier-Stokes (LES/RANS) and Analytical Methods for Far-Field Acoustics	Reasonable	Feasible but Not Applicable for Sound Reflections in the Acoustic Domain
CFD-BEM	CFD Simulations (LES/RANS) Coupled with Helmholtz Equation via Boundary Integral Equation (BIE) Form	Good	CFD Computational Expense Feasible For Large-Scale Applications

- Complex plume path (through mobile launch ducts, deflection under ML, plume exiting flame trench)
- Reflection, diffraction, attenuation of acoustic waves on ML and tower structures
- Selected BEM as most suitable for complex launch pad topology

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FastBEM CAA

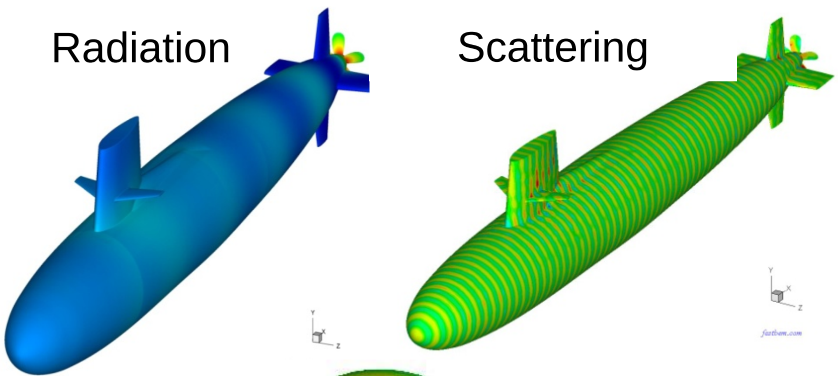
- Evaluation of implementation of BEM method for hybrid CFD/CAA is underway
- Facilitated through NASA Small Business Technology Transfer project (STTR) to utilize technology from existing software: **FastBEM Acoustics** (Prof. Liu, U. Cincinnati)
- FastBEM Solves Helmholtz Equation via Boundary Integral Equation (BIE) Form
- Fast multi-pole BEM for solving 3-D, interior/exterior, radiation/scattering problems with velocity, pressure and impedance BCs
- Fast Multi-pole Method (FMM) reduces the cost (CPU time & storage) for BEM to $O(N)$
- Demonstrated fast and accurate wideband acoustic analysis from low to high frequencies without compromising the BEM model size and accuracy
- Large-scale acoustic BEM models with unknowns (DOFs) up to several millions solved on PCs and even larger models on supercomputers

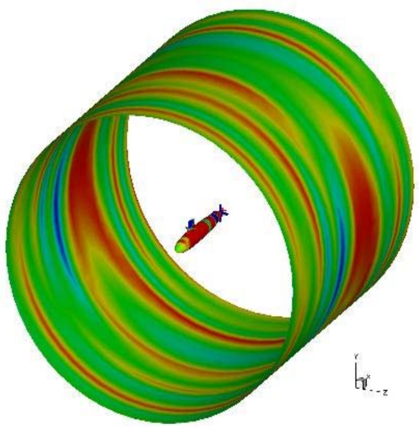
FastBEM Examples

Radiation Due To Propeller Vibrations

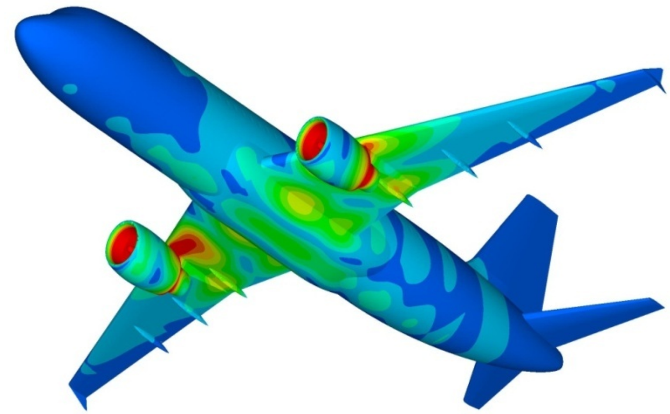
Radiation

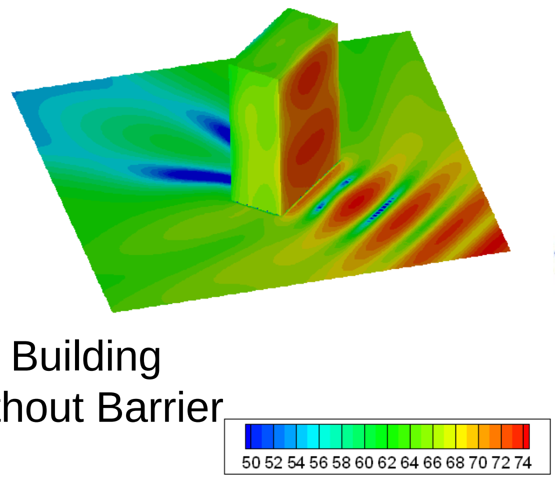
Scattering





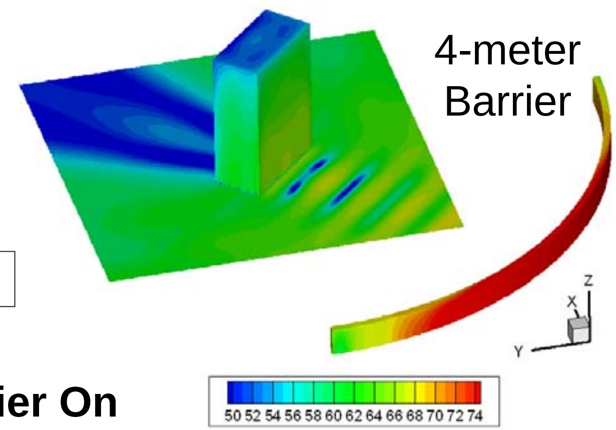
Radiation Due To Engine Vibrations





Building
without Barrier

4-meter
Barrier



Effect Of Sound Barrier On Noise Level (dB) On Building

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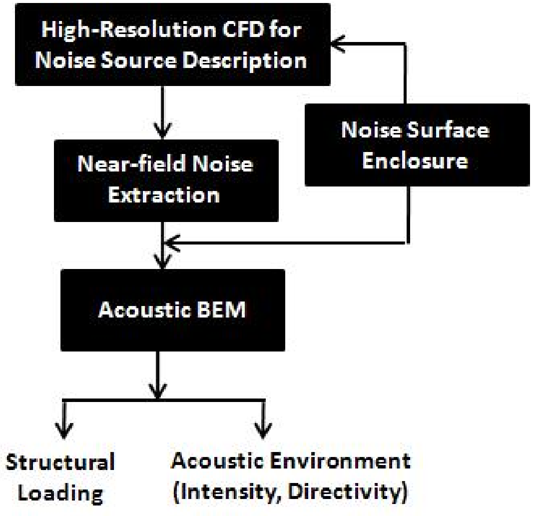
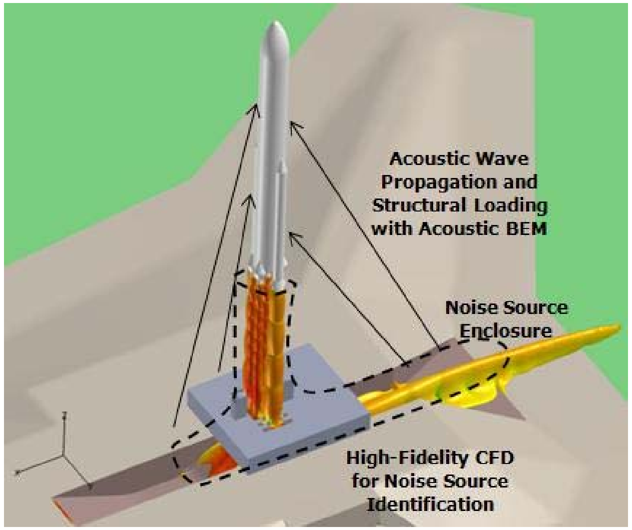
Liftoff CFD-CAA Process Implementation

- Establish process to extract source surface enclosing acoustic noise source regions
  - Complicated enclosure surface result from plume interaction with structures
  - Explore approaches to automating enclosure generation
- Develop handover process of acoustic enclosure surface to FastBEM input BC utilizing existing Loci/CHEM native post-processing tools
- Demonstrate FastBEM software capability to analyze complex launch pad topology
  - Large domain, complex enclosed structures topology
  - Port software to NASA supercomputer facilities
- Validate process against standard acoustic experiments (supersonic plumes, etc.)
- Identify modifications and improvements for NASA specific applications





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CFD-CAA Process Validation and Maturation

- Upon successful completion of proof-of-concept and process development, enter phase of establishing production capability for NASA problems
- Identify adequacy of existing Loci/CHEM modeling accuracy for generating high quality noise source data to extract on enclosure surface
- Identify best practices guidelines for CFD simulation to achieve proper resolution of noise sources
  - CFD simulation grid density, time-step resolution, turbulence modeling
  - Placement and resolution of enclosed source surface for proper handover of acoustic source characteristics
- Demonstrate and validate tools and process for relevant cases
- Prime candidate is ASMAT: highly instrumented, both dry and wet simulations available
- Welcome suggestions and cooperation with CFD-CAA community for suitable validation cases

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Conclusions

- MSFC Fluid Dynamics Branch responsible for NASA liftoff environments
- Sophisticated, validated CFD analysis capability in place for liftoff flow environments (pad and flame trench aerothermal, IOP, debris transport, …)
- Now extending CFD analysis to predict liftoff noise
- Intent is to apply CFD to capture effects not included in empirical liftoff acoustic methodologies: plume impingement, flame trench plume interaction, water deluge, …
- Selected hybrid CFD-CAA approach to retain benefits of multi-physics CFD capabilities
- Selected BEM approach for CAA because of capability to capture interaction with complex launch pad topology
- Development under way to establish CFD-to-CAA data extraction and exchange process
- Extensive demonstration and validation planned for realistic launch pad cases (e.g., ASMAT)