Garry Lyles

14 March 2008

Thrust Oscillation Focus Team
Checkpoint Report

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TOFT Charter

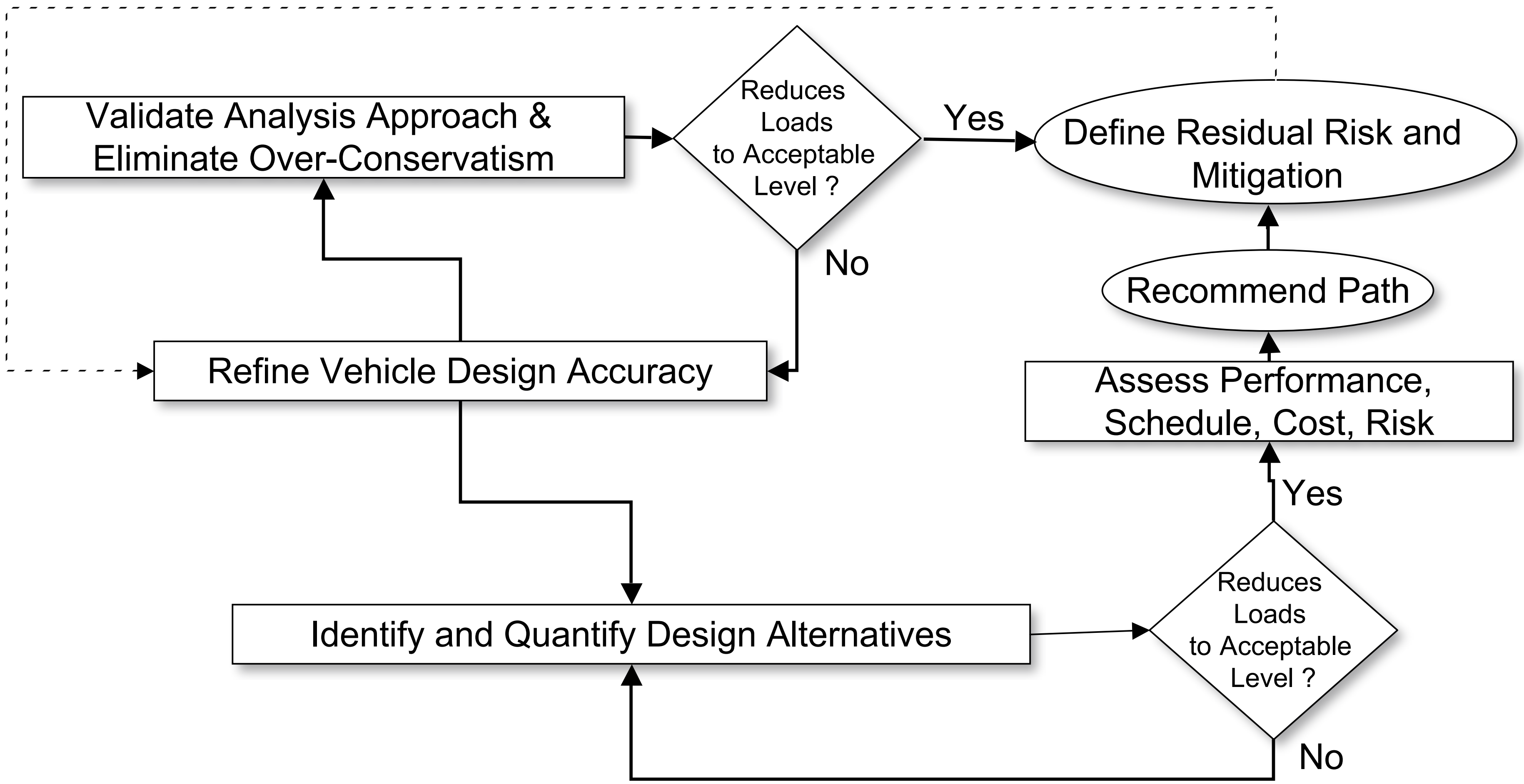
- **Charter a Thrust Oscillation Focus Team (TOFT) to:**
  1. Review the forcing functions, models and analysis results to verify the current predicted dynamic responses of the integrated stack
  2. Identify and assess options to reduce predicted responses
  3. Validate and quantify the risk to the Ares I vehicle, Orion spacecraft, crew, and other sensitive subsystems and components to the extent allowed by the Ares I/Orion design maturity
  4. Establish and prioritize mitigation strategies and establish mitigation plans consistent with the CxP integrated schedule
- **The TOFT will deliver the above assessment no later than the March CxP PDR Checkpoint and provide weekly status updates.**
- **The TOFT membership will consist of centers discipline engineering, Ares and Orion systems engineering, Vehicle Integration, the NESC, Aerospace Corporation, ATK, and identified national discipline experts**
- **The TOFT will conduct a kickoff TIM on 15 and 16 November to review current analyses and historical data and to develop a detailed forward plan for concurrence by the PSE and Ares Project**

Thrust Oscillation Focus Team
Team Membership

- Leads - Garry Lyles / Eli Rayos (ILSM SIG)
- Chief Engineer's Office - Leslie Curtis
- Vehicle Loads Analysis- Jeff Peck / Isam Yunis / Pravin Aggarwal
- Vehicle Controls Analysis - Steve Ryan
- Motor Analysis - Tom Nesman / Jonathan Jones / Dan Dorney / Jeremy Kenny / ATK Engineering (Tyler Nester / Terry Boardman)
- Ares Vehicle Systems Integration - Rob Berry (Element Integration Lead)/ Bob Werka (Global Mitigation Lead)/ Belinda Wright / James Sherrard
- Orion Systems Engineering - Chuck Dingle / Corey Brooker / Thomas Cressman (SM) / John Stadler (LAS) / Tom Goodnight (SM) / Keith Schlagel (LM)
- Ares Systems Engineering - Joe Matus (US) / Rick Ballard (USE) / Wendy Cruit (FS)
- Safety and Mission Assurance - Ho Jun Lee / Chris Cianciola
- Crew and Human Factors - Phil Root / Bernard Adelstein

- NESC Structures and Dynamics Team - Curt Larsen / Alden Mackey
- NESC Consultants - Scott Horowitz / Gloyer-Taylor Labs (Paul Gloyer, Tim Lewis, Gary Flandro, Fred Culick, Vigor Yang)
- Independent Structural Dynamics Discipline Experts - Hal Doiron / Bob Ryan / Luke Schutzenhofer / George Zupp / Ken Smith / Jim Kaminski / Jim Blair / George James
- Boeing - Ted Bartkowicz / Steve Tomkies
- Shuttle Booster Project Engineering - Mike Murphy / Steve Ricks / Sam Ortega
- Aerospace Corporation - John Skratt / Kirk Dotson , et al
- Pratt and Whitney Rocketdyne - Tom Kmiec / Steve Mercer

Roadmap


Validate Analysis Approach & Eliminate Over-Conservatism
Reduces Loads to Acceptable Level ?
Yes
Define Residual Risk and Mitigation
No
Recommend Path
Refine Vehicle Design Accuracy
Assess Performance, Schedule, Cost, Risk
Yes
Identify and Quantify Design Alternatives
Reduces Loads to Acceptable Level ?
No

Thrust Oscillation

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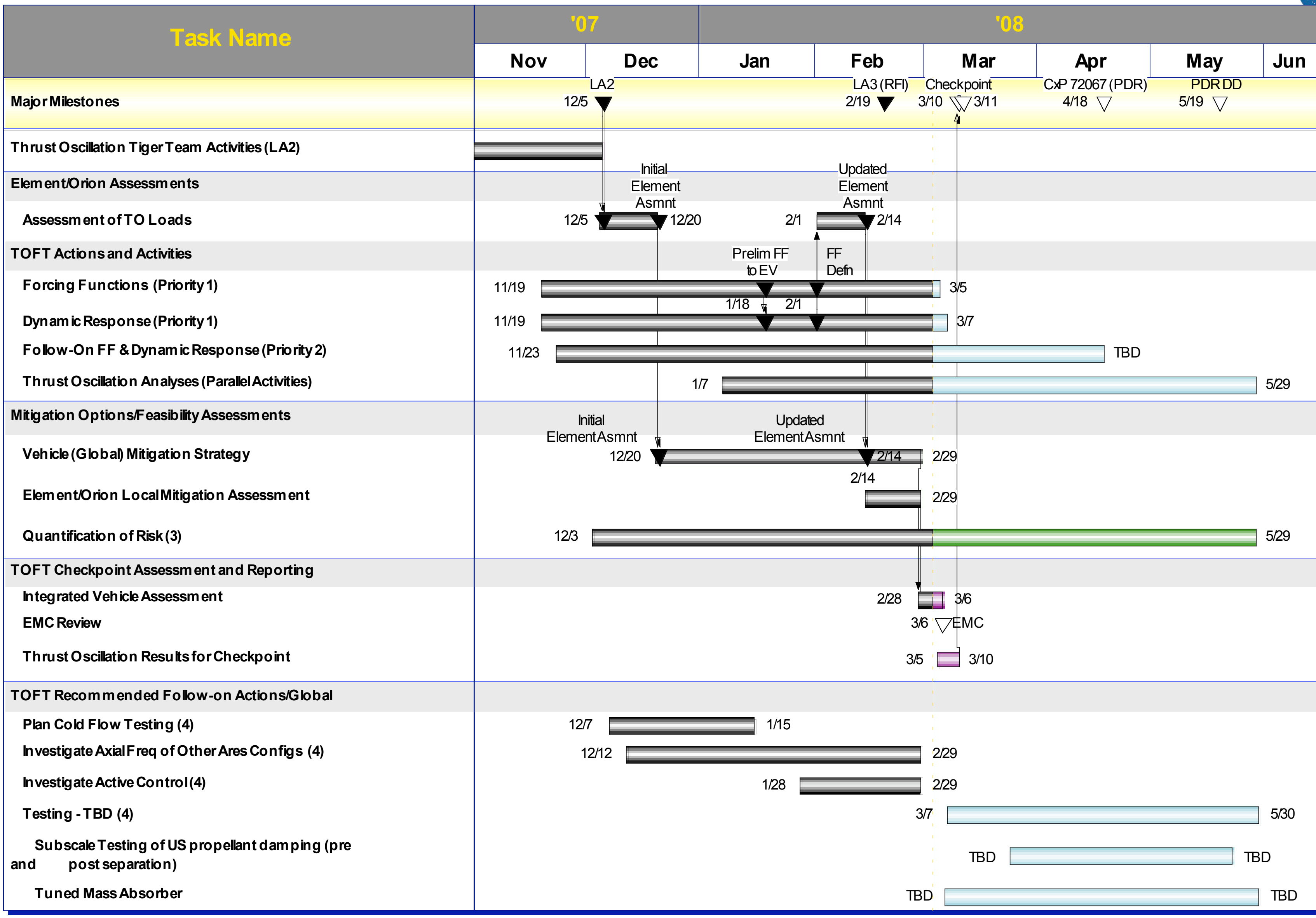
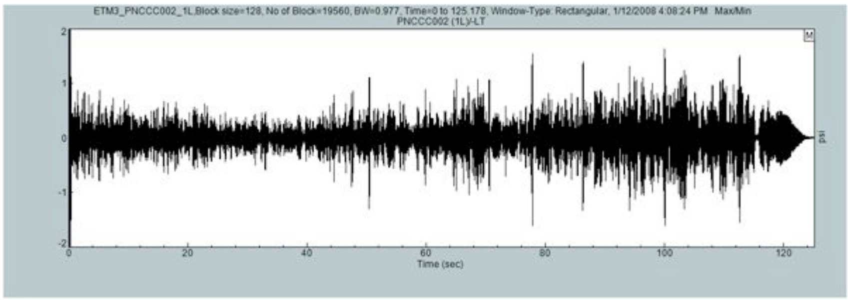
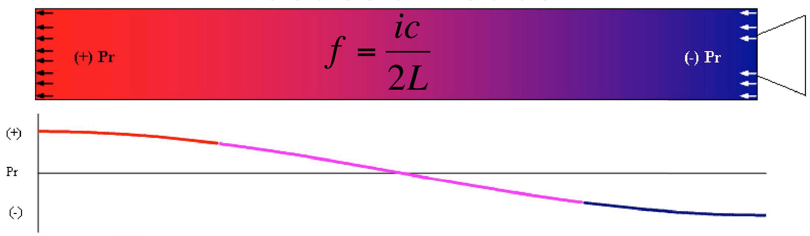


Motor Test Data -> Forcing Function -> Structural Response

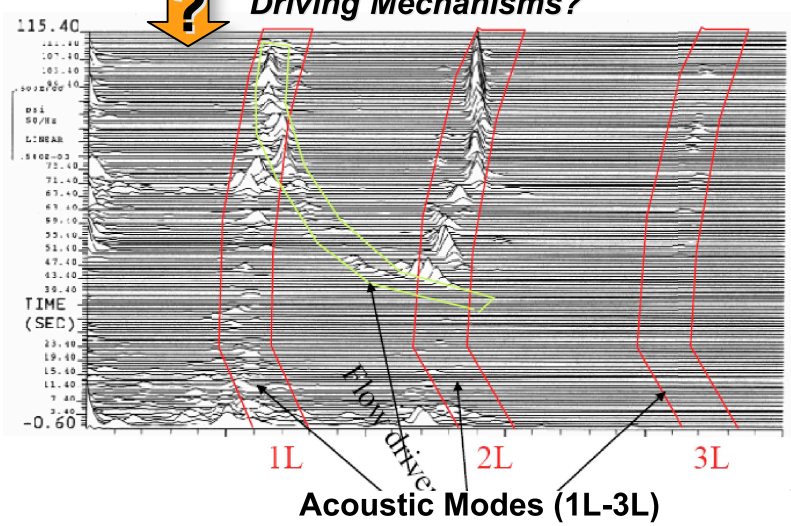
Motor Test Pressure



Acoustic Modes



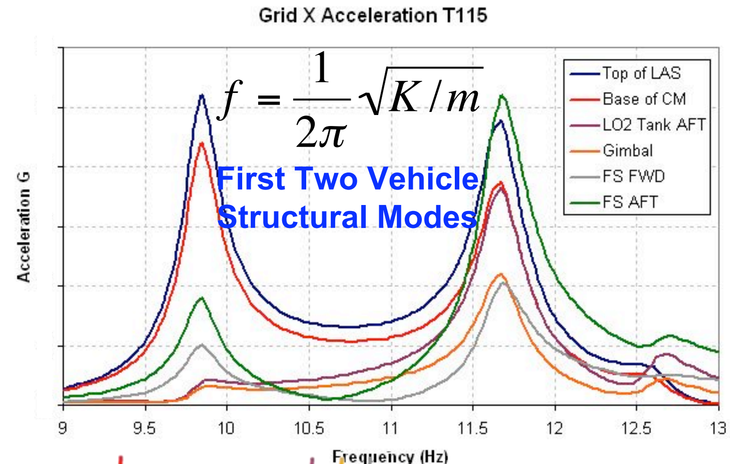
Driving Mechanisms?

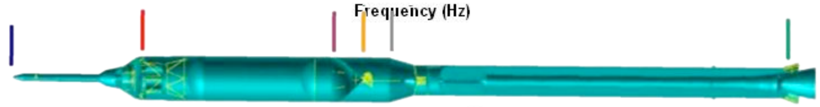


Data Distribution? Dispersions?

Population Anomalies? 4 to 5-segment Conversion?

Structural Response

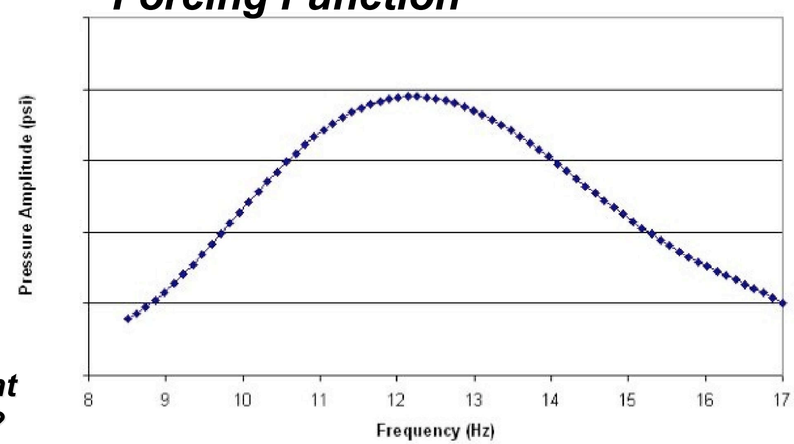




Pressure to Thrust Conversion? Transfer Function? Dynamic Uncertainty? Damping Factor?

110-120 s 1L = 12.14 Hz

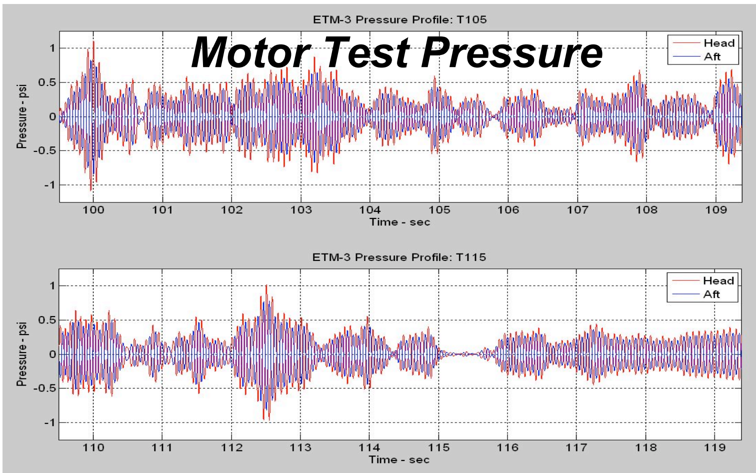
Forcing Function

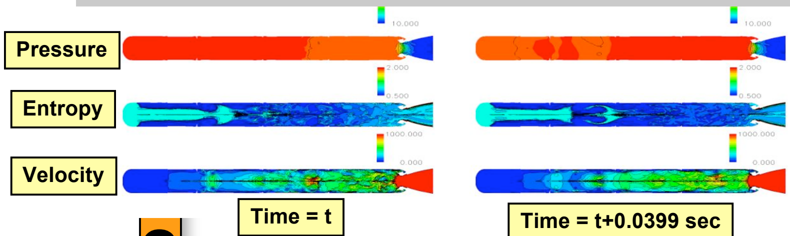


Actions Summary

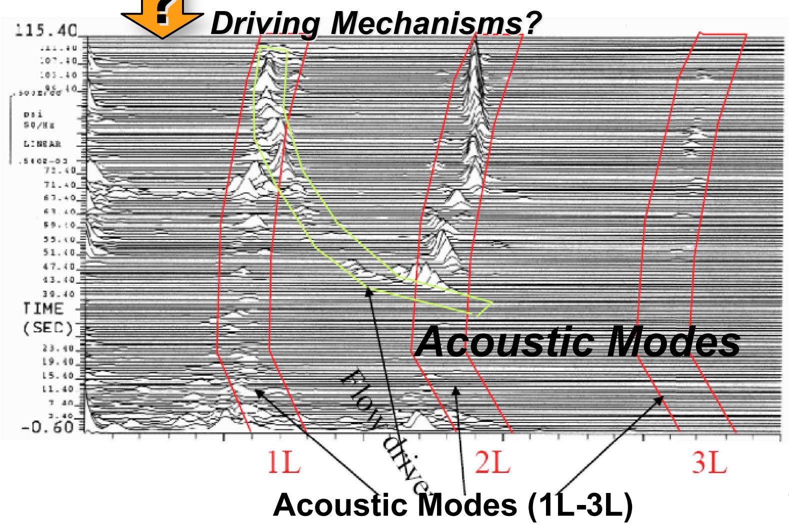
- ✓ **Determine the appropriate nominal and dispersed forcing function.**
  - √ Clarify the effects of the nozzle and internal geometry
  - √ Compare frequency-domain methods with time-domain methods and quantify conservatism
  - √ Clarify statistical description of data
  - • Clarify difference in flight and ground test data - *need flight data*
- ✓ **Verify and validate the vehicle loads model.**
  - • Force application - *need flight data*
  - √ Load combinations
  - • Appropriate application of damping and axial stiffness - follow-on analysis
- ✓ **Conduct near-term evaluations of element subsystems' sensitivity to dynamic loads**
- ✓ **Evaluation candidate global mitigation and local mitigation as sensitive subsystems are identified.**

Motor Test Data -> Forcing Function -> Structural Response

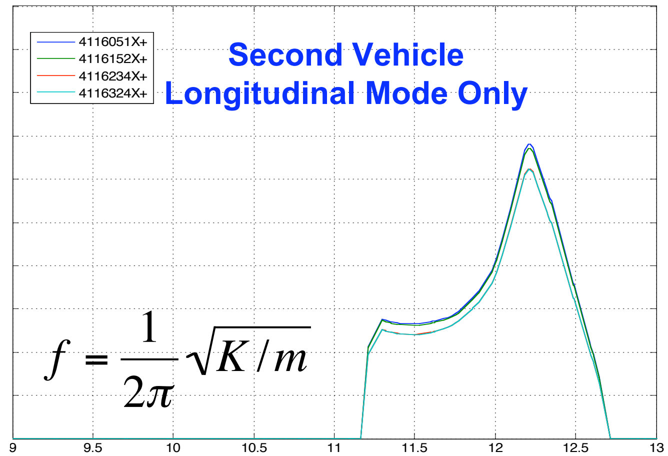




$$f = \frac{ic}{2L}$$



Structural Response

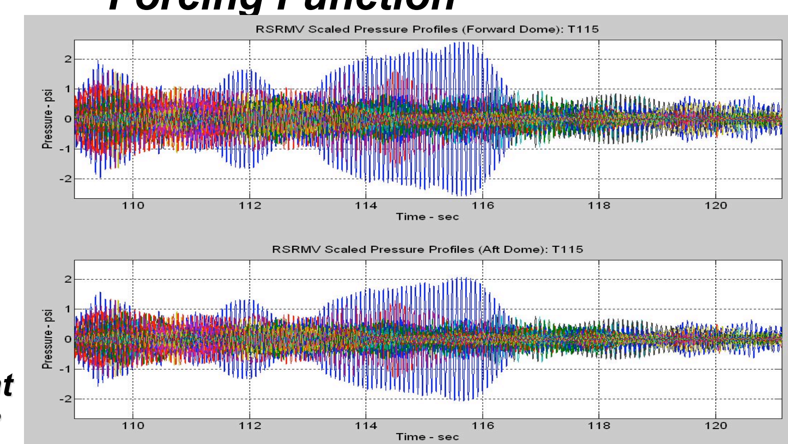


Pressure to Thrust Conversion
Transfer Function?
Dynamic Uncertainty
Damping Factor?

Data Distribution Dispersions?

Population Anomalies?
4 to 5-segment Conversion?

Forcing Function



Action Results

- **Over-conservatism reduced**
  - 1.5 - 2X reduction from original 5 December accelerations
  - Removed 1st longitudinal mode as an issue
  - Includes 14 - 20% reduction due to nozzle effects
- **Conservatism still remains**
  - Forced tuning within + / - 10% of 2nd longitudinal mode - 20% vs untuned
  - Damping may be conservative (Damping is something that is hard to quantify. The 1% modal damping is the historical starting place. It requires a lot of testing develop and verify higher modal damping values.)
    - No propellant damping accounted for - early subscale, smooth tank data indicates ~50% increase in local damping
    - No composite structure damping accounted for (e.g. Frustum) - 15% total vehicle increase estimated for local increase at frustum
    - Motor nozzle may provide significant damping
  - 99.865 at 90% confidence - ~ 30 - 40% reduction at 99.
  - Still may be internal motor findings that will reduce dispersions - STS-9A adds 30% to dispersions
- **Ares and Orion design/FEM changes can have an effect on thrust oscillation - integrated solutions must be accomplished**

Action Results - Continued

- **Crew location usually follows centerline accelerations but divergence has occurred as internal Orion configuration changed**
- **First Stage, Upper Stage, and Upper Stage Engine: no major impacts from thrust oscillation loads but lox tank aft dome may need to be strengthened and more analysis is needed on the MPS effects at staging.**
- **Orion and Crew require mitigation. Orion will have to make changes to stiffen SM tanks (TO is a driver - current design can handle 4 + / - .5 g requirement)**
- **First Stage internal motor physics is much better understood but cold flow and sub-scale hot fire testing is required prior to motor design changes**
- **Shuttle Flight data is needed to:**
  - Clarify differences in flight and ground test data
  - Quantify forcing function and vehicle response analysis
  - Determine crew seat environments

Action Results - Continued

- **Mitigations options could reduce TO by at least 10X**
  - Active counter pulsing - 0 to ~ 1000 lb payload and addition testing and verification
  - Internal motor changes - FS schedule impact due to cold flow and sub-scale testing
    - Eg., “Castle Top” inhibitors
  - Vehicle configuration change
    - 4-segment, 3-J2Xd5 - significant reliability hit but detunes system
    - Other changes may provide performance margin to mitigate TO - e.g., increase FS nozzle AR, expendable FS
- **Mitigation options to reduce loads/accelerations on Orion**
  - Mechanical isolation at Ares/Orion and FS/US
  - Tuned mass absorber (> 2X - 3X reduction)
  - Local isolation in CM will be required in combination with global mitigation to meet performance spec of .14 - .3 g’s (.25 g from Mercury/Gemini).
  - <u>All options require integrated analyses</u>

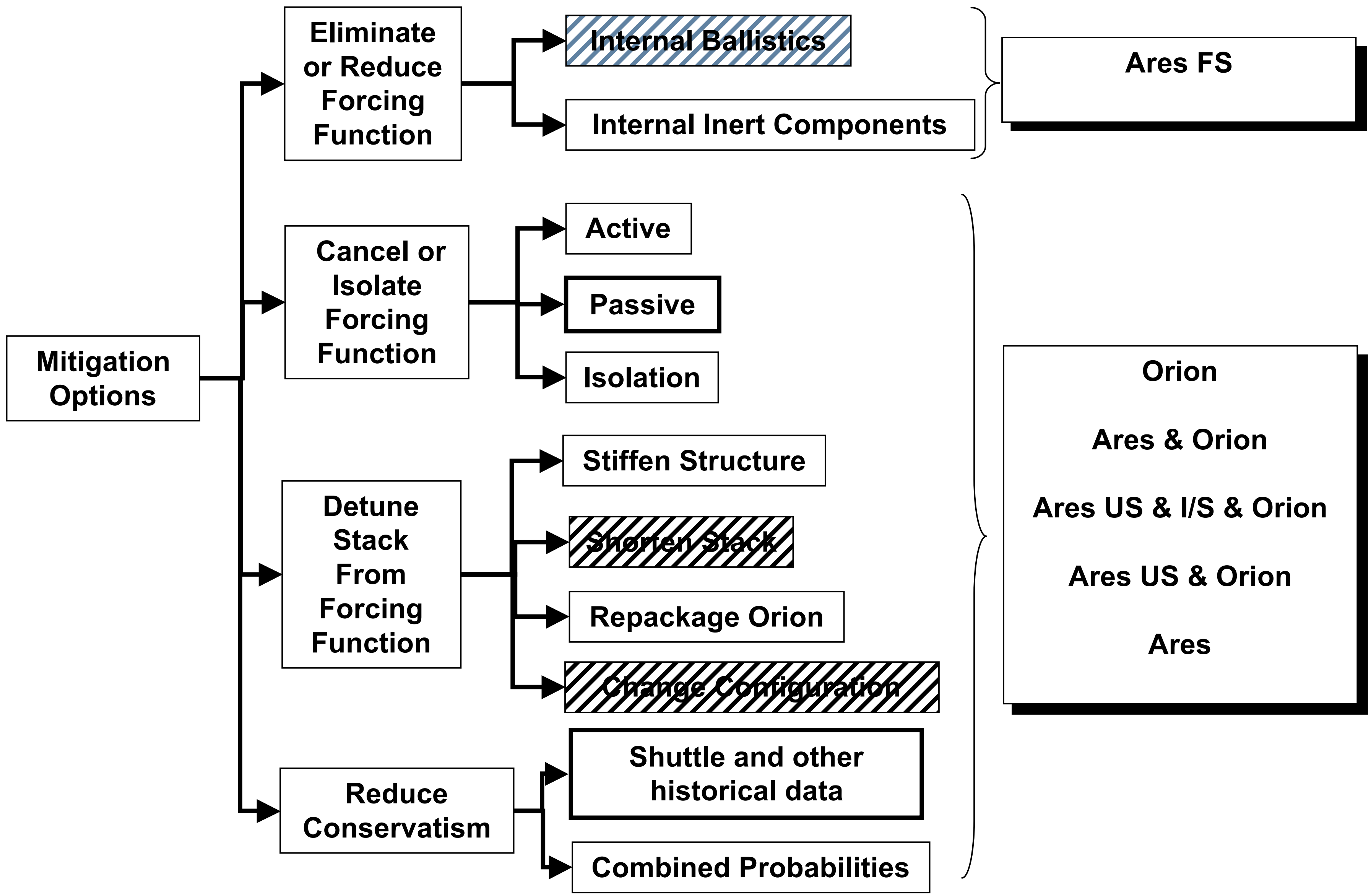
Near-term Actions Closed

- ✓ **Supply new set of forcing functions - 14 - 20% reduction due to nozzle effects. Continuing to investigate RSRM to RSRMV gains**
- ✓ **Validate models and forcing function**
- ✓ **Run New Integrated Vehicle Response**
  - ✓MSFC - Time domain tuned within + / - 10% of 11.7 Hz 2nd longitudinal mode - delivered on 03/07
  - ✓GRC - Look at encapsulated Orion
  - ✓LaRC - Monte Carlo delivered 03/05 - assessment required before generating loads
  - ✓JSC/Boeing - independent check of frequency and time domain (tuned and untuned) - delivered on 03/07
  - ✓Run 99.865 at 99% - delivered 03/07
- ♦ **Continue analysis of internal motor options**
  - Gloyer-Taylor Labs will deliver recommendation on internal motor mods to eliminate pressure oscillations - Preliminary recommendations provided
  - CFD result maturing to look at "castle top" inhibitor - Preliminary - analysis is continuing
- ♦ **Continue to look at the feasibility of the tuned mass absorber**
- ♦ **CSA Engineering to provide a design for isolating the US / Orion**
  - Preliminary results provide delivered on 03/07
- ♦ **HS crew performance spec - .14 - .3 g - need further trades and evaluation**
- ♦ **IVGVT hardware fidelity requirement needs evaluation**

Summary

- **The natural maturing of the vehicle design and the explicit management of critical design parameters can detune the system and reduce loads**
  - Frequency will naturally move lower with stiffness and increasing mass
  - Damping should increase due to both knowledge of the current configuration and through explicit design decisions
- **The probability that the maturing design will move the system response below the crew spec is not known today. There are limits to the design changes that can be proposed.**
  - Integrated structural design is a complex balance of all loads, controls and performance and the current margins are not sufficiently robust to allow any design change to avoid TO loads
  - Test data will be required to verify the design and implementation of global design changes
- **Design and requirements changes that can be implemented now with relatively low impact (scar) would ensure margin in the design that could be traded for performance in the future as the design matures**

Mitigation Trade Space



Assessment of Design Options
Eliminate or Reduce Forcing Function

♦ Effectiveness

- Eliminate TO at the source (forcing function)
  - First Stage carries most of design changes (local mitigation of some subsystem, e.g., SM tanks)
  - Preliminary estimates show ~ 50 - 90% reduction in energy content of vortices
  - Eliminating all TO is probably unachievable - pyrolytal vortices will continue

♦ Risks

- High risk due to schedule impact and late verification of design changes
  - Changes to motor and their effect on TO not fully understood
  - Testing and analysis needed to further define needed changes
  - Mitigation options would need to be carried through development and would create large cost and schedule impacts if incorporated.

Assessment of Design Options
Detune Stack from Forcing Function

♦ Effectiveness

- Detune the vehicle 2nd longitudinal modes
  - Lower frequency would be lowest risk option
  - Requires ~10% frequency shift
  - Loads reduction benefit can easily be 5X

♦ Risks

- Vehicle will naturally migrate to lower frequency due to weight increase and reduced stiffness
  - Design changes require IVGVT
  - Would require multiple small design solutions that are currently undefined
  - Would impact lateral stiffness, loads and control
  - Structural changes to move frequency is complex - as stiffness is reduced, mass is decreased and counters effect $f = \sqrt{k/m}$

- Increase vehicle damping
  - Current critical damping factor may be conservative
  - Assess damping from existing design
    - US Propellant
    - FS frustum and nozzle

- Localized damping can be tested early and incorporated into model, but uncertainty in the overall vehicle damping will remain until IVGVT/Ares 1-Y.
  - IVGT must have fidelity of the local design changes
  - Significant risk to cost and schedule due to late verification
  - Loads reduction will be <= 2X

Assessment of Design Options
Cancel or Isolate Forcing Function

♦ Effectiveness

- Mechanical Isolation
  - Except for Orion full encapsulation approach, most of isolation carried on Ares Upper Stage side of interface (Orion SM tank change required)
  - More maturity in approach if implemented at the Orion/Ares compared to US/FS
  - Would reduce loads to well within crew health limits
  - Still would not meet performance limit

♦ Risks

- Performance / Control impacts
  - May reduce payload by 500 - 1500lbm
  - Reduces lateral stiffness unless mitigated in the design
  - Adds failure modes
  - Changes system modes for loads and control

- Tuned Mass Absorber
  - First Stage carries most of design changes (Orion SM tanks change required)
  - Use existing mass to counterbalance TO
  - $\geq$ 2X reduction for passive system
  - $\geq$ 3X reduction for active system
  - Payload impact less than other concepts ($\leq$ 100 lbm)

- Immature design
  - May create problems for FS recovery system
  - Active control design is immature
  - Reduces loads to well below human health limit, but not performance limit.
  - Adds failure modes
  - Changes system modes for loads and control

- Active Pulse Thrusters
  - First Stage carries most of design changes (Orion SM tanks change required)
  - Could provide 10X reduction in TO
  - Relatively mature thruster design
  - Self-contained
  - Relatively mature control system

- Performance and aft skirt design challenge
  - ~ 0 - 1000 lbm payload impact
  - Trade required for separate and booster deceleration
  - Add failure modes
  - Must survive aft skirt environments

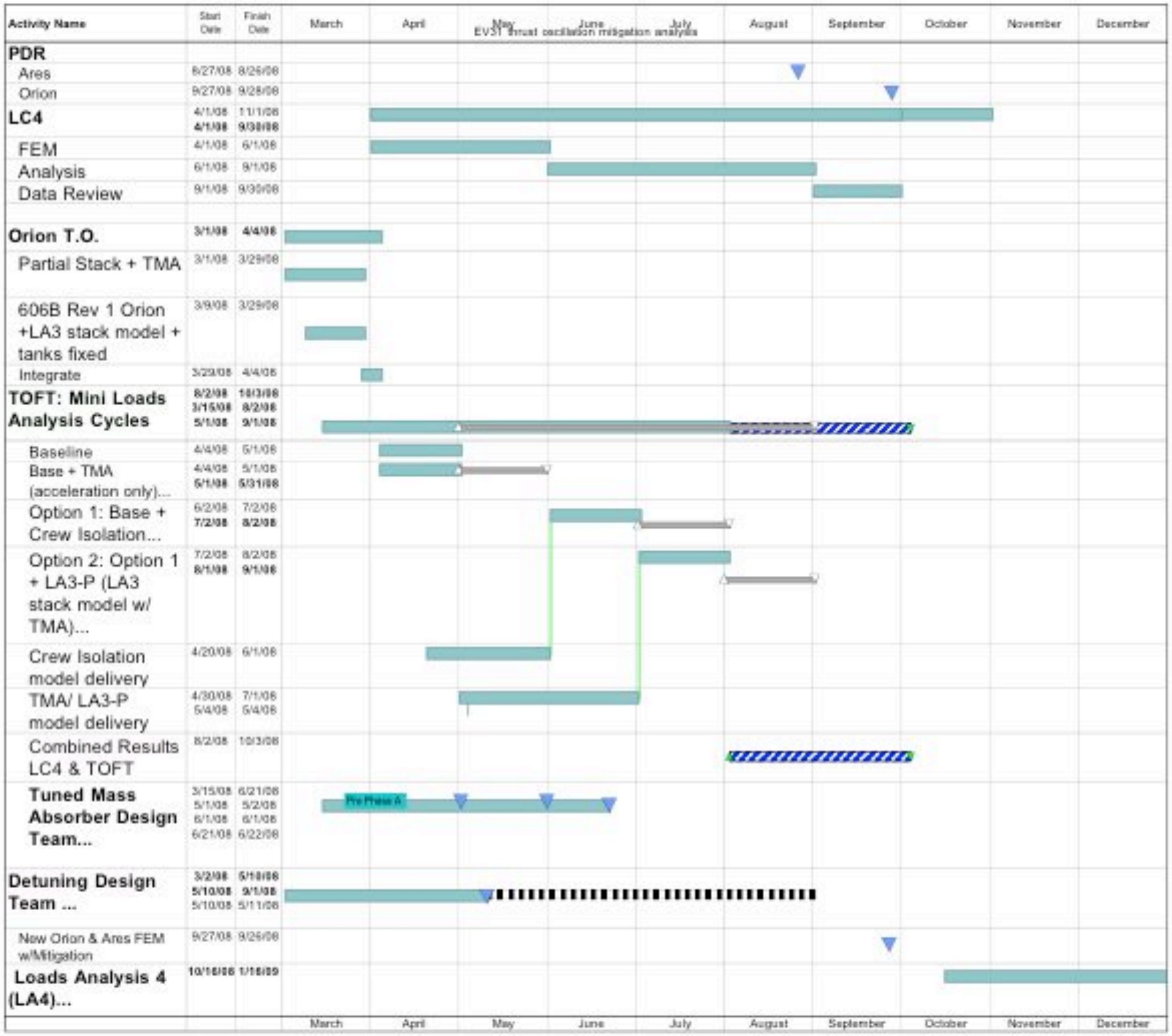
Recommendation
Leading up to PDR - Parallel Efforts

- **Initiate Pre-Phase A design of the Tuned Mass Absorber**
  - Provide input to coupled loads cycle below as concept matures
  - Complete by PDR
  - Conduct analysis and trade study of the Pulsed RCS concept and Isolation concepts to mitigate residual risk of the Tuned Mass Damper
- **Stand up an integrated coupled loads team to perform 1-month iterative mini loads assessments consistent with mitigation options above (parallel to LC4).**
- **Deliver a set of thrust oscillation loads and frequency constraint/range avoidance via a CxP Management Directive to the Projects/elements based on the above**
- **In parallel, stand up a small (6 person core - 8 person support) integrated design team to propose design concepts to de-tune system frequencies. <u>Include assessment of the encapsulated Orion</u>. Deliver initial design recommendations in 6 weeks**
- **Evaluate SRM internal design modifications after GTL final recommendation and consider cold flow / subscale testing to support a future block upgrade**

Follow-on Recommendations

- **Continue to obtain data to accelerate system knowledge and remove conservatism**
  - Instrument Shuttle and Ares 1-X to verify internal pressure to force transfer functions
  - Instrument Ares 1-Y and Orion 1 to define internal pressure to force transfer functions and dispersions
  - Make acquisition of this data a primary objective for the above flight test
  - Implement analysis and ground test plan for propellant damping and composite damping
  - Data from above sources will increase the data sample used to define the pressure-time histories and dispersions
  - Develop integrated verification requirements for IVGVT
- **Conduct integrated trade study of crew performance requirement that includes a probabilistic approach to monitoring capability during the short flight time of the TO environment**

Thrust Oscillation Mitigation Path

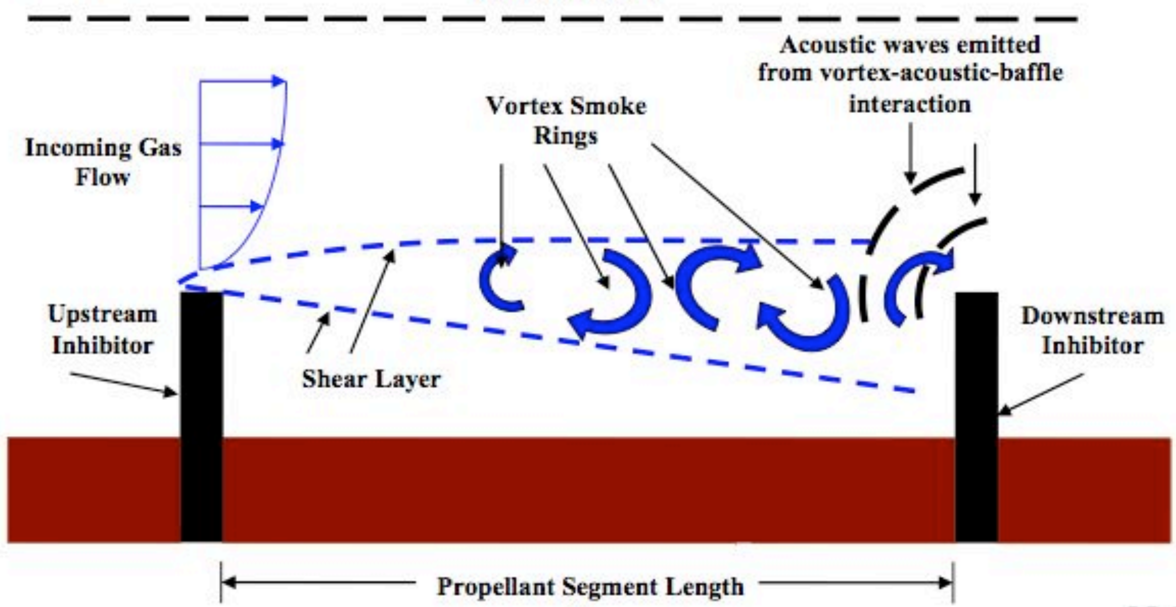


Backup - Supporting Charts

Scaling Factors

Scaling Factors-Osc. Amplitudes-Cont.

- Sinusoidal Noise Sources
  - Vortex smoke rings shed from upstream inhibitors in the flow convect downstream and interact with the downstream inhibitor, creating sound.



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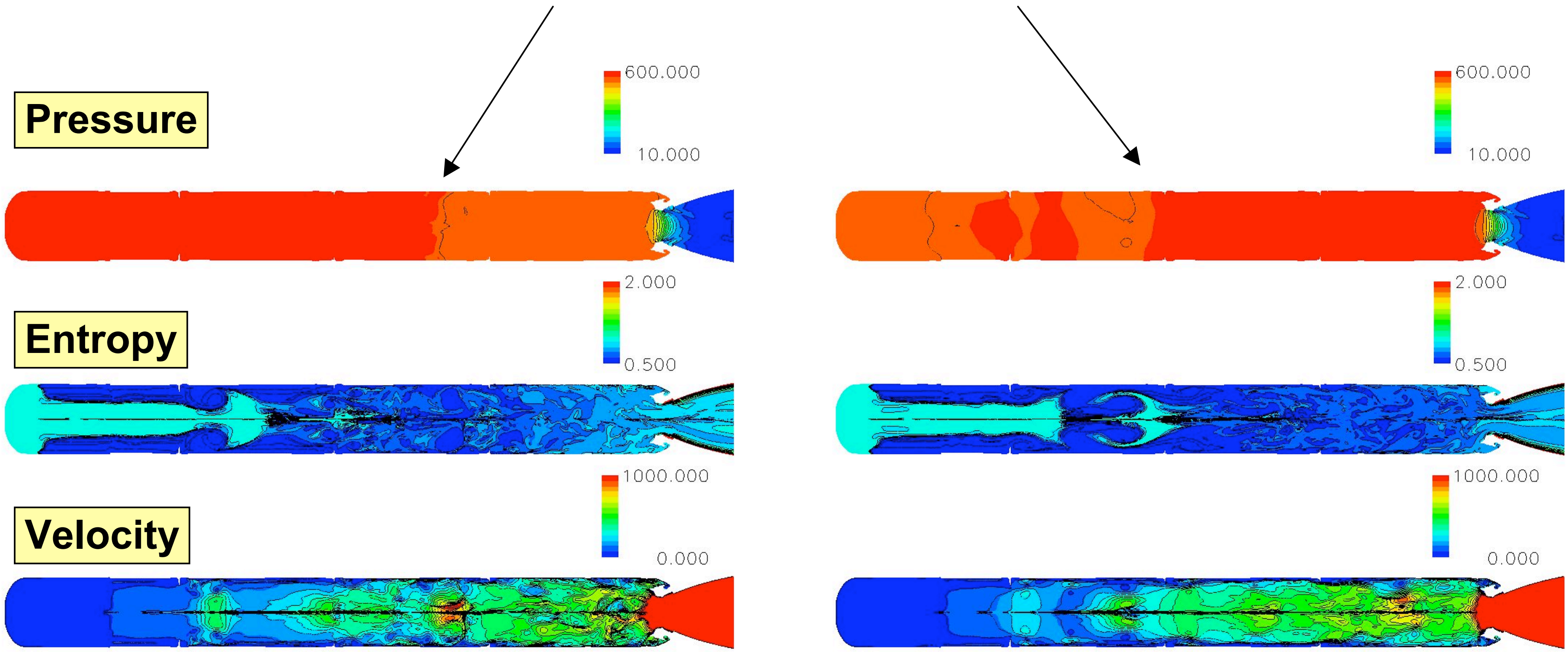
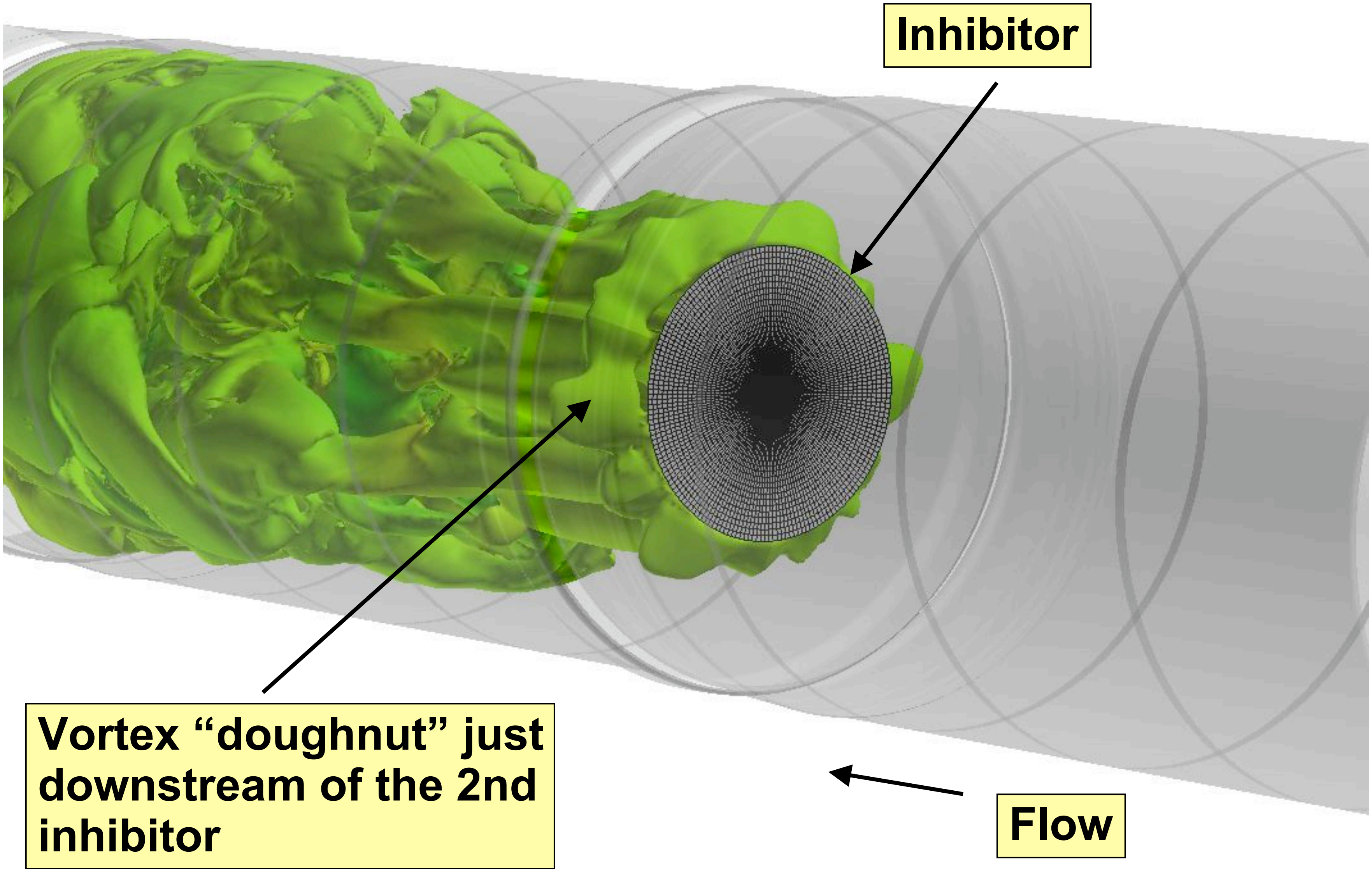
Pressure (psi), Entropy, Velocity(ft/sec)

Note movement of pressure wave

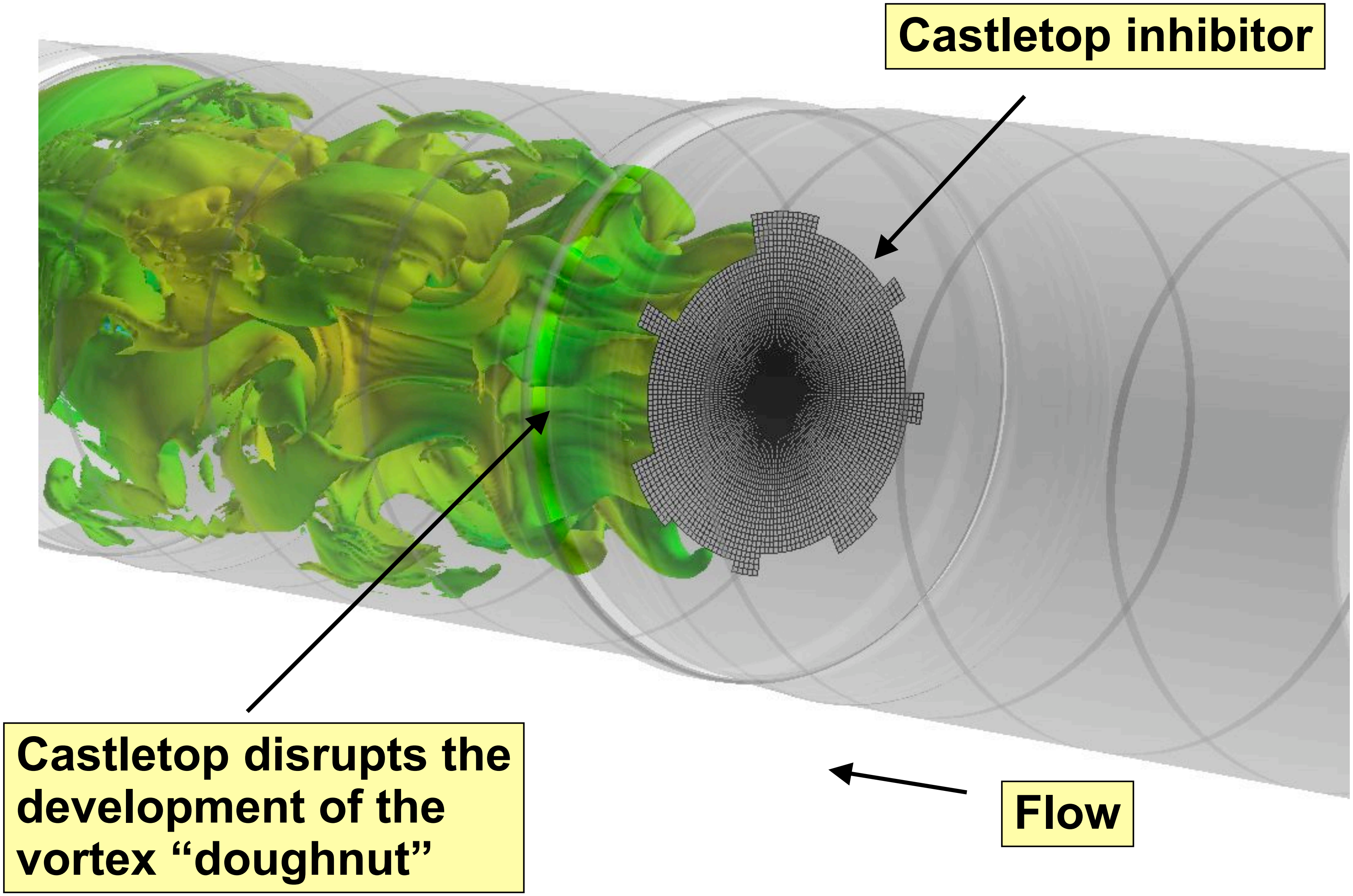


Time = t **Time = t+0.0399 sec**

Original 2nd Inhibitor (No Castletop)

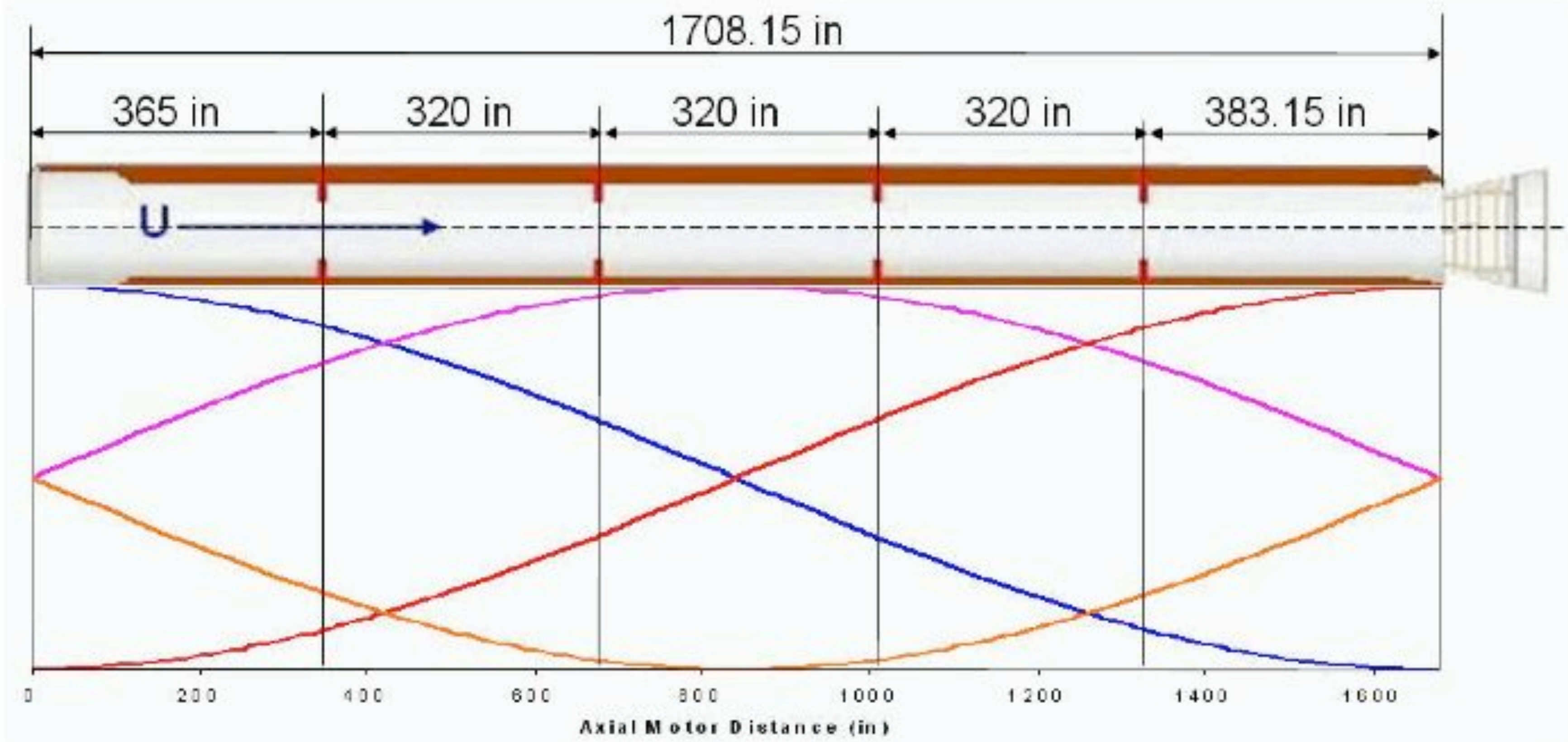


Effects of Adding Castletop to 2nd Inhibitor



Scaling Factors-Osc. Amplitudes-Cont.

- RSRMV Mode Shapes



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