Aeroacoustics of Space Vehicles

Jayanta Panda
NASA Ames Research Center
Moffett Field, CA

Presentation for
Applied Modeling & Simulation (AMS) Seminar Series
Building N258, Auditorium (Room 127), NASA Ames Research Center
Moffett Field, CA

April 8, 2014
Definition Aeroacoustics

Aeroacoustics for Airplanes
- Mostly for community noise reduction
- Very few vibro-acoustics concerns (such as failures of nozzle cowlings)

Aeroacoustics for space vehicles
- Mostly for vibro-acoustic concern
- Intense vibrational environment for payload, electronics and navigational equipment and a large number of subsystems
- Community noise - little concern until recent time
- Environment inside ISS – separate issue

Fig. 1 Shuttle payload bay vibration and acoustic environment sources.
Typical levels (dB) of surface pressure fluctuations on launch vehicles

- 150 dB
- 160 dB
- 170 dB
- 180 dB
- 185 dB

Loud Rock Concert
Max Level inside Crew cabin
Threshold of ear pain
Inside flame trench
Shock-plume interaction
Pad/low altitude abort
High altitude abort?

20 dB = X10
40 dB = X100
60 dB = X1000

Protuberances, Separated flow regions
Smooth parts of vehicle
Level inside cargo, payload fairing
Transonic Oscillating shock
Base of Vehicle
Tip of Vehicle
Launch Acoustics
Abort Acoustics
Ascent Acoustics

Saturn V, Space Shuttle, 70t Block I crew, 130t Block II cargo
The end goal of acoustic analysis is to predict structural responses due to acoustic loads.

3.1 Acoustic-Load Parameters

To the extent required for design, the predicted acoustic loads shall be given as a function of position and time in terms of:

- Overall sound-pressure level
- Frequency spectrum
- Spatial correlation

2.2 Vehicle Loading

The minimum description of the loading on the vehicle, needed to estimate the structural response, is given in terms of the detailed distribution on the structure of the sound-pressure spectrum. A more detailed description also requires the spatial correlation pattern of the sound-pressure field to enable more exact vibration prediction. Such analyses are required for examining certain types of failures, such as the sonic fatigue of lightweight external panels.
Aeroacoustics: part of Fluids – Structure Interactions

NASA CR-1596: Himelblau, Fuller, Scharton, “Assessment of space vehicle aeroacoustic-vibration prediction & testing”

\[ G_{w}(x, f) = A^2 G_{pr}(f) \sum_{i=1}^{\infty} \sum_{k=1}^{\infty} \frac{\phi_{i}(x)\phi_{k}(x)H^{\ast}(f)H_{l}(f)j_{ik}^{2}(f)}{(2\pi)^{4}f^{2}f^{2}\mu_{i}\mu_{k}} \]

where the cross-joint acceptance function is given by

\[ j_{ik}^{2}(f) = \left[A^2 G_{pr}(f)\right]^{-1} \iint_{A} G_{p}(\xi, \xi', f)\phi_{i}(\xi)\phi_{k}(\xi')d\xi d\xi' \]

- Modelling via splitting the problem into aero-acoustics and vibro-acoustics

---

Jay Panda (NASA ARC)
Separation of fluid dynamics and structural dynamics
- Aero-acoustics as a part of combined load

**Forcing function** - Distribution of Auto and Cross-spectra of acoustic pressure fluctuations

\[
G_{12} = G_d(f) \sin(k_0d) / k_0d
\]

\[
G_{12} = G_p(f) e^{-c_d k_t d} \left[ \cos(k_t d) - i \sin(k_t d) \right]
\]

Diffused Acoustic Field

Progressive Wave Field

\(G_d = \text{DAF autospectrum}\)
\(G_p = \text{PWF autospectrum}\)
\(k_t = \omega / U_t = \text{trace wavenumber}\)
\(k_0 = \omega / c_0 = \text{acoustic wavenumber}\)
\(d = \text{separation distance}\)
\(c_d = \text{correlation decay coefficient}\)

**Prediction of Structural response** - forcing functions input to structural dynamics analyses - FEM, BEM, SEA models of the components, systems and subsystems of the vehicle.
Vibro-Acoustics tests for flight certification

One of the 25Hz horns in the test chamber

Reverberant Acoustic Test Facility
NASA Plum Brook Station

Mechanical Vibration Facility
Roadmap:

- Launch Acoustics
  - Description of launch pad
  - Prediction, CAA
  - Static fire test
  - Flight test
  - Identification of acoustic sources During Antares launch by a microphone phased array
    - not discussed – Ignition over pressure (IOP)

- Ascent Acoustics
- Abort Acoustics

Other minor sources (not discussed)
  - vent noise
  - pressure fluctuations during reentry, etc.
Why study launch acoustics?

- Very high acoustic level during launch creates high vibro-acoustics environment
  - All payloads, many parts of the vehicle, and ground op systems need to be designed, tested and qualified for this environment
  - The fluctuation levels influence the weight and the cost of the vehicle

- The acoustic suppression systems needs to perform optimally to provide relief
Launch pad design and acoustic suppression system

- Deflector
- Trench/Duct
- Mobile launch platform
- Service Tower
- Water flow systems
- Vehicle trajectory
  - elevation
  - drift

Shuttle Pad water injection

- There exists no prediction methodology from the fundamental equations
- Total acoustic power $W_a$ is related to the mechanical power $W_m$ generated by the rocket, $\eta = \text{efficiency factor} \ 0.2\% \text{ to } 0.8\%$

$$W_a = \eta W_m = \eta \sum_{\text{All nozzles}} 0.5 (\text{Thrust}) U_{\text{exit}}$$

Distributed source along plume path

![Diagram showing distributed source along plume path]
Prediction - based on flight data from prior vehicles

Acoustic data books
- Apollo – Saturn
- Space Shuttle
- Ares-IX

- Scaling based on engine thrust, and Strouhal frequency.

Challenges –
⇒ Complex geometry, high Re, multi-phase flow, multiple $\gamma$, multiple species

Paths for CAA simulation:
● RANS + acoustic analogy
● LES
● Need of experimental data for validation

Pressure pulse after Ignition, J. West, MSFC

LES simulation: Fukuda et al, 2009
Effect of water injection: Fukuda et al, 2011
Model scale static fire tests - ASMAT

Static fire tests are the best means to determine:
- launch environment
- water schedule
- pad modification

- 5% scale model of ARES I
Validation/adjustment from Flight sensors

External microphones on Orbiter
What are the true sources of noise during liftoff?
- Use of microphone phased array

- Phased array – Acoustic camera, a tuned ear.
- Ubiquitous in Aeronautics, new in Space applications
- Need for a large size array for a full-scale vehicle application
  → Angular resolution of array ~ (acoustic wavelength) / (array aperture)

- Design of a brand new array
  ► 10’X10’ size, use 70 microphones
  ► lighter weight
  ► weather protection
  ► debris protection
  ► vibration isolation for camera

Microphone pattern for new 10’ array
Evolution of phased array project

- Array validation in **Ames hybrid motor test**
  - revealed the need for solid state electronics
  - vibration isolation
  - need for rain protection

- Software
  - Conventional beamform
    \[ b_{jj}(f) = w_{j,m}^* G_{m,m}/ w_{j,m}/ \]
  - Spectral Element Technique (SEM) provided most promise
    \[ E(\alpha_j, f) = \sum_{m,m'/=1}^J \left| G_{m,m'} - \sum_{j=1}^N w_{j,m} \alpha_j^2 w_{j,m}'^* \right|^2 \]

- All hardware shipped to NASA Wallops

Noise map during hybrid motor burn
Phased array set-up at Wallops pad 0A

Instrumentations:
- 70 condenser microphones
- 1 visible band camera
- 1 long wave Infra-red camera
- 1 x-y accelerometer

The phased array was mounted on a scissor lift at south side of pad 0A, ~400’ from the Antares Engine, & 40’ above ground
Phased array in Antares A-one launch: April 21, 2013
Acoustic Attenuation Systems

- Water injection inside launch mount (on the top of the flame trench).

On-deck water injection using 4 Rain-bird heads

- Water started to flow from 3 short and 1 long rainbirds
Initial Trajectory
- Slow moving vehicle
- TEL avoidance maneuver to avoid contact with the service tower

Time dependent beam-forming:
- Microphone time signals were segmented into 0.2s wide segments

Propagation delay:
- Microphones received the launch events at a delayed time. ~ 0.4s for sounds to propagate from the launch pad to the phased array.
Noise source map at t+0.6s, conventional beam-form at 2kHz

Source strength at 2kHz in 80Hz wide band - Auto-scaled

- Engine Ignition created noise source at launch mount
- Phased array, mounted 40’ above ground, saw both the primary source and its image on ground
The duct (trench) exhaust became the primary noise source as the hot plume started to come out (see movie).

Effective cooling by duct water minimized the extent of the noise source – the OASPL was somewhat reasonable.

Launch mount remained as a strong noise source.
Vehicle drifted even more towards east, caused heavy spreading of the hot plume over the pad, extended the size of the noise source. 

Start of flow from short 3 Rainbirds (not much water). No flow from 1 tall rainbird. Duct water in full force.
• The long, exposed plume was the primary noise source.
• Still some impingement on the pad, yet the rainbird system had come to full force, and quenched the hot plume and the deck.
• From this time on, as the vehicle gained altitude and speed, the acoustic level on the vehicle was expected lower; however, ground service equipment did not see any decrease for another few seconds
• ground reflection

Jay Panda (NASA ARC)
Optimization of Antares Water injection schedule

Hi Jay,
Yes the activation timing of the water deluge rainbirds was moved up from T+5s to T+3.8s.

Subject: Re: Antares Test Launch

Understood, thanks. Yes from a ground system standpoint, we also noted less ablative wear on the launch mount this time around, which is most likely attributable to faster water deluge activation. The phased array effort was indeed beneficial.
Ascent Acoustics

- Vehicle trajectory and dynamic pressure
- Buffet and acoustics
- Prediction – empiricism and existing database, CFD
- Wind tunnel tests
- Shape modification
- Flight tests
Surface pressure fluctuations are directly proportional to the flight dynamic pressure:

\[ P_{\text{rms}} = k q \]
Prediction - Aerodynamics of Launch Vehicle

Fig 16  Shuttle aerodynamic flow field – Mach 0.9

Fig 17  Shuttle aerodynamic flow field - Mach 1.46
Prediction - steady state CFD to determine input parameters for empirical relations

Attached turbulent boundary layer:

\[ p_{rms} = q \frac{0.01}{1 + M^2} \]

Use CFD database to determine boundary layer
Displacement thickness \( \delta^* \)

Calculated auto-spectra using empirical relations
Prediction - steady state CFD to determine input parameters for empirical relations

USM3D calculated flow-field over ARES IX at flight $M = 1.6$ (Source: Steve Bauer LaRC)
Prediction - based on flight data from prior vehicles

- Falls apart when vehicle shape changes
Wind tunnel tests and scaling Laws

Table 17. Rigid buffet model scaling laws.

<table>
<thead>
<tr>
<th>Quantity to be Scaled</th>
<th>Full-scale to Model-scale Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>( P_{fs} = P_{ms} \frac{Q_{fs}}{Q_{ms}} )</td>
</tr>
<tr>
<td>Force</td>
<td>( F_{fs} = F_{ms} \frac{Q_{fs}}{Q_{ms}} \left( \frac{D_{fs}}{D_{ms}} \right)^2 )</td>
</tr>
<tr>
<td>Time</td>
<td>( T_{fs} = T_{ms} \frac{D_{fs}}{D_{ms}} \frac{V_{ms}}{V_{fs}} )</td>
</tr>
<tr>
<td>Frequency</td>
<td>( f_{fs} = f_{ms} \frac{D_{ms}}{D_{fs}} \frac{V_{fs}}{V_{ms}} )</td>
</tr>
</tbody>
</table>

Pressure PSD (psi²/Hz)

\( \phi_{fs}^{(P)} = \phi_{ms}^{(P)} \left( \frac{Q_{fs}^{(P)}}{Q_{ms}^{(P)}} \right)^2 \frac{D_{fs}}{D_{ms}} \frac{V_{ms}}{V_{fs}} \)

Force PSD (lbf²/Hz)

\( \phi_{fs}^{(F)} = \phi_{ms}^{(F)} \left( \frac{Q_{fs}^{(F)}}{Q_{ms}^{(F)}} \right)^2 \left( \frac{D_{fs}}{D_{ms}} \right)^5 \frac{V_{ms}}{V_{fs}} \)

Space Launch System (SLS) test at NASA Ames Unitary

What to do if measured fluctuations are very high? – cost and weight penalty
Real Engineering – What if the acoustic levels are too high?
MPCV Shape Optimization to Reduce Aero-acoustic environment
MPCV Shape Optimization to Reduce Acoustic environment

(a1) 605- baseline M = 0.95
(b2) ALAS11 M = 0.95
(c2) ALAS11+taper (rev3) M = 0.95
(d2) ALAS11+blend M = 0.95

(a3) M = 1.6
(b3) M = 1.6
(c3) M = 1.6
(d3) M = 1.6

Sensor Name
Sensor Name
Sensor Name
Sensor Name
MPCV Shape Optimization to Reduce Acoustic environment

(c) rev3-22p5-noSM runno:610 at M:0.90
(d) rev3-22p5-noSM runno:619 at M:1.80
(e) rev3-noSM runno:418 at M:0.90
(f) rev3-noSM runno:456 at M:1.80

AOA

Full scale OAFLP dB

1 2 3 4 5 6 7 8 9 10 11 12 13 14

140 145 150 155 160 165

sensor name
Comparison with Data from Flight Test – ARES-IX
Reed et al. AIAA 2011-174

- In general reasonable comparison
- Discrepancies near changes in outer mold line geometries.
- Zones near protuberances show poor comparison
- Data from supersonic part of the flight show poor comparison
- Flaws in the scaling laws?? Reynolds number effect?
Buffet – fluctuations in aerodynamic forces:

- Fluctuations in force = integration of pressure fluctuations
- Force fluctuations in 1-20Hz may cause coupling with global bending and/or torsional modes of the vehicle.
- May lead to catastrophic failures
- Typically occurs at transonic speed: $0.8 \leq M \leq 1.1$
- Primary cause: shock oscillation coupled with large separated flow.
- Mitigation - Restriction/Minimization of separated zones.
  - fixing oscillating shocks.

Matt Knapp, TLG Aerospace
Abort Acoustics

- Problem definition
- Wind tunnel simulation, CFD
- Flight test

Apollo Abort test
ORION/MPCV and the Launch Abort System

(a) ORION/MPCV

Launch abort tower
abort motor nozzles
Boost Protective Cover (BPC)

(b) Launch Abort System

Heat Shield

Mach 0.300, Alpha 0.00
Mach 2.000, Alpha 0.00

Abort Acoustics

Jay Panda (ARC-AOX) 650-604-1553
Prediction –

• Initial prediction Based on SP-8072 – Not dependable

• No prior experience from Mercury or Saturn programs
• All microphones burnt out in one flight test
Measurement of plume-generated noise in the static test of MPCV launch abort motor ST1
Results from ST1

- No prior aerospace structure was subjected to this high level of dynamic load

- Very high level
- High freq dominated
- Non-linear, shock dominated
How to create acoustic environment for Abort?

- Single flight tests are unsuitable to create a design environment
- we needed to know levels over $0 \leq M \leq 4$ and $10^\circ \leq \alpha, \beta \leq -10^\circ$
- Requires transonic supersonic wind tunnel to simulate forward flight
- Hot Helium to simulate plumes from rocket motors
Why hot-Helium?

- Hot He reproduces acoustically relevant parameters: **speed of sound, velocity, density.**

Pressure fluctuations at a point $X$ on LAV (Ffowcs-Williams, 1965):

$$p(X, \tau) = \frac{1}{2\pi} \int_V \frac{\partial^2 T_{ik}}{\partial Z_i \partial Z_k} \left( Z, \tau - \frac{r}{c} \right) dZ$$  \hspace{1cm} (1)

$$T_{ik} = \rho u_i u_k + \delta_{ik}(p - c^2 \rho)$$  \hspace{1cm} (2)

- Validation from prior small-scale tests:
  - SRM vs. He: Morgan & Young (1963)
  - Papamoschou (2007), Greska & Krothapalli (2009)

- Practicality of operation:
  - Suitable in a wind tunnel.
  - Use of high fidelity model with all 4 nozzles.
  - Survivability of the kulite sensors

- Cost effective means of creating 80 abort conditions.

- Primary differences between He and rocket plume:
  - Lack of afterburning;
  - Absence of $\text{Al}_2\text{O}_3$ particles;
  - Different $\gamma$
Matching between wind tunnel and flight conditions

\[ \frac{p_f}{p_t} = f \left( \frac{D_{er} D_{jr} \alpha_r \beta_r M_{jr} M_{er} (p_e/p_a)_r c_{jr} \rho_{jr} \rho_{er} U_{jr} U_{er} (J_e/J_o)_r W_{er} q_f q_{jr}} {D_{eh} D_{jh} \alpha_h \beta_h M_{jh} M_{eh} (p_e/p_a)_h c_{jh} \rho_{jh} \rho_{eh} U_{jh} U_{eh} (J_e/J_o)_h W_{eh} q_t q_{jh}} \right) \]
Abort initiated at M 1.6: Influence of forward flight

Distibution of turbulence intensity

$M_a = 1.6$, $\alpha = -10^\circ$, $\beta = -10^\circ$

CFD by: William J. Coirier, Kratos/DFI
Abort initiated at M 1.2: Influence of forward flight

Wind tunnel pressure fluctuations need to be scaled to flight condition
- problem of two different ratios of dynamic pressures:
\[
\frac{p'(\text{model})}{p'(\text{flight})} = f\left(\frac{\text{Dynamic press tunnel}}{\text{Dynamic press flight}}, \frac{\text{Dynamic press Helium plume}}{\text{Dynamic press Rocket plume}}\right)
\]

- Each abort condition was simulated by two Helium + Wind tunnel setup:
  - Nozzle exit match
  - q-ratio match
• Test conducted in the NASA Ames 11-Ft Unitary Plan wind tunnel

• Mach Range 0.3 – 1.2

• Reynolds Number: $2 \times 10^6$ - $5.0 \times 10^6$/foot,

• He pressure at Model Plenum: 300psi to 600psi

• He temperature at Model Plenum: 660F to 700F

• Internal piping for 11 different model attitudes:

![Graph showing (alpha, beta) points](image-url)
Project Orion: Crew Exploration Vehicle (CEV)

- He Accumulator
- Jumbo trailers
- Cold He Supply
- Flue stack
- STAHL air intake
- Impedance heater on He line

Abort Acoustics

Jay Panda (ARC-AOX) 650-604-1553
Abort Acoustics

11 ft test section
Model and Instrumentation

- 6% scaled of LAV 606 F.1
- Continuous active cooling of the model core
- Subjected to very large temperature cycle – periodic heating and cooling.
- 237 Kulite sensors
Sample Result: Run 184: $M = 0.3$, $Re = 3e6$, $\alpha=0$, $\beta=0$
Effect of Forward Flight

M = 0.3

M = 0.6

M = 1.2
Pad Abort-1 is a NASA flight test of a system that could be used to rescue a crew and its spacecraft in case of emergencies at the launch pad.

www.nasa.gov
Comparison with Pad Abort 1 flight data

Pad Abort test flight PA1:
- Happened on July 2010 from White Sands
- Full scale unmanned flight vehicle, old Mold Line,
- accelerated from M 0 to ~ 0.7 over the burn duration.
- 57 sensors distributed over lower tower and Party-hat

- Not exactly apple-to-apple comparison
  - Older, slimmer profile
  - **Flight:** transient data, **wind tunnel:** steady state
  - Wind tunnel: No Attitude Control Motor
80AS show wider crest-trough variation than PA1
- PA1 flew with non-zero $\alpha$, $\beta$
- PA1 had ACM induced turbulence
Comparison with PA1 flight data – q scaling

- Along Plume axes
- In Between Plumes

**Normalized PSD: \( \frac{(\rho^2 q_j^2)}{(\Delta f D/U)} \)**

- **80AS:K171, M:0.30**
- **80AS:K171, M:0.39**
- **80AS:K171, M:0.49**
- **80AS:K171, M:0.50**
- **80AS:K171, M:0.60**
- **80AS:K171, M:0.69**
- **80AS:K171, M:0.70**
- **PA1:cs003v**

- **80AS:K172, M:0.30**
- **80AS:K172, M:0.39**
- **80AS:K172, M:0.50**
- **80AS:K172, M:0.60**
- **80AS:K172, M:0.70**
- **80AS:K172, M:0.29**
- **80AS:K172, M:0.49**
- **80AS:K172, M:0.70**
- **PA1:cs004v**
Existing uncertainties:

- Scaling laws for abort initiated at transonic/supersonic flight
- Increment in environment due to scattering of plume by vehicle induced shock waves

Expecting further validation from another flight test
- Ascent Abort 2 (AA2) – Abort initiated at M ~ 1.1
Summary:

Basics

- For launch vehicles aeroacoustics is a part of fluid-structure interaction problem
- Separation into Aeroacoustics and Vibro-acoustics
- Aeroacoustics = surface pressure fluctuations
- Forcing functions for vibro-acoustic calculations
  - overall level – extremely high
  - auto-spectra
  - cross-spectra
- Need for direct solution of fluid-structure interaction.

Launch Acoustics

- Complexity of launch pad – acoustic suppression systems
  - deflector and trench design
  - vehicle trajectory and drift
  - amount of water injection and timing schedule
- Prediction via NASA SP-80672 & limitations
  - ignores plume impingement, water injection, vehicle drift
- Prediction via flight data from prior launch vehicles
  - very large spread, different for a new vehicle
- Limited ability of CAA
- Use of a microphone phased array for direct identification of noise sources
  - Very different description of noise sources that SP-8072
Summary:

Ascent Acoustics
- Source - turbulent flow over vehicle surface, local flow separation, unsteady shocks
  - dynamic pressure and vehicle trajectory
- Prediction – identification of local flow separation and transonic/supersonic shock wave.
  - Improvement of empiricism via input from CFD
  - Future need for less empiricism - CFD?
  - Data from prior flight experiences
- Wind tunnel test - validation/verification
- Change of vehicle OML to reduce ascent acoustics – MPCV experience
- Limitations observed from flight data

Abort Acoustics
- Lack of prior experience and database
- Creation of database from Static Fire test – spectral trends, shock amplitude
- Challenge of simulating hundreds of abort scenario within a reasonable budget
  - Hot helium to simulate rocket plume
    - similarity parameters
    - scaling problems
  - Increasing Flight Mach shows a reduction in overall levels, but increases low freq content.
  - Plume impingement generally reduces level of pressure fluctuations
- Comparison with flight data from Pad Abort 1:
  - Not an apple-to-apple comparison: different shape, transient flight vs steady simulation
  - Nonetheless, comparable overall level and the spectral shape
- Unique, one-of-a-kind test provides aeroacoustics environment for the design and qualification testing of ORION/MPCV Launch Abort Vehicle.
BACKUP
Summary:

● Unobstructed plume: noise sources are distributed along the plume
● In a launch configuration: locations where plume impinges on solid surfaces are the primary sources

► Current Lift-off models (SP8072) does not account for impingement
  - Need investments in changing/updating these models
► Minimization of plume impingement will attenuate liftoff environment
  ○ By reduce vehicle drift in early part of liftoff
  ○ Possibly by increasing the MLP hole size

● Open/Uncovered part of the trench are noise sources
  ○ Closing the trench as much as possible will reduce liftoff environment

● Water injection in the hole & trench is effective in reducing trench generated noise
● On-Deck water (Rainbird) is partially effective in noise source mitigation

● Microphone phased-array is an ideal tool to study all launch acoustic environments
  - Results from the current study are expected to help SLS pad design

Future work:
Looking for opportunities to use phased-array in full-scale launch
Reference:
4. Apollo flight environment data book – ref??
Fig 4  Typical ascent flight trajectories

Figure 1.3-2. STS Aero/Acoustic Noise Level Time History - Crew Cabin - Flight Deck
Summary of results from Engine Test:
- The primary noise source was the duct exit
- Plume out of the duct exit was NOT a primary source - very large amount of water pumped at the duct inlet quenched the flame
- Noise generated during impingement on the deflector, and general mixing inside the duct, emerged out of the duct exit.
- First time application of phased array in full-scale engine test