Acoustic Model Testing Chronology

ER42/ Tom Nesman

Spacecraft and Launch Vehicle
Dynamic Environments Workshop, June 20-22, 2017
Introduction

Scale models have been used for decades to replicate liftoff environments and in particular acoustics for launch vehicles. It is assumed, and analyses supports, that the key characteristics of noise generation, propagation, and measurement can be scaled. Over time significant insight was gained not just towards understanding the effects of thruster details, pad geometry, and sound mitigation but also to the physical processes involved.

An overview of a selected set of scale model tests are compiled here to illustrate the variety of configurations that have been tested and the fundamental knowledge gained. The selected scale model tests are presented chronologically.
Early acoustic model testing (1950’s) explored a multitude of deflector, launch duct, and launch pad configurations.

These early tests also tried various water sprays … initially for cooling but an additional benefit, reduction in acoustics, was observed.

Later, vehicle specific acoustic scale model testing was conducted.
1959 Rocket/ Pad Acoustic Model Studies


- Model solid fuel rocket & supersonic cold air jets
  - Both give same *qualitative* trends
- Multiple launch pad designs versus noise level
- Low frequency octave band levels increasing relative to overall sound levels as the vehicle rises
- Sound field of full scale rocket duplicated only by using a model rocket which duplicates rocket exhaust conditions
- Type of launch pad has little effect on sound levels when vehicle reaches a height of 4 *equivalent nozzle* diameters above pad
- Also noted effects from:
  - Jet impingement angle
  - Introduction of water from deflector surface
  - Elbow deflector with water
  - Deflected multiple nozzles
  - Interaction of multiple supersonic air jets
Overall Sound Level Comparison

Other Deflector & Scaling Aspects


• Scaling model to full scale
  – Model rocket data compared to full-scale with comparable specific impulses and chamber pressures showed a reasonable agreement in absolute magnitude and spectrum shapes by using a frequency scale factor equal to the square root of the relative thrusts

• Atmospheric sound absorption
  – Noted air absorption losses for small acoustic models, e.g., on the order of 5 dB at 50 KHz at a distance of 10.0 feet

• Investigators at this time evaluated physical relationships by comparison of measured data from model and full-scale firings and concluded:
  – Scaling and prediction techniques can provide a reasonable estimate of launch environment
  – There is a relationship between the generated sound energy and the kinetic exhaust stream energy of the rocket engine
  – Prediction of a noise spectrum can be made from engine nozzle diameter and exhaust velocity
1961 Model Acoustics Scaling

Similarity for a scale model near field noise:

– Similarity of noise generation
– Similarity of flow
– Similarity of noise propagation

Rules to obtain comparable sound levels at scaled frequencies

– Maintain same $p'$ within flow ($\rho \cdot U_c^2$)
– Maintain same source velocity characteristic relative to ambient

$$\rho \cdot u^2 \cdot \frac{U_c}{c_c} \cdot \frac{c_c}{c_0}$$

– Observation from same angle and source diameters from source
– Maintain same geometry of source and nearby reflecting surfaces

$$\frac{p_{r,\theta}^2}{\left(\rho_j \cdot U_j^2\right)^2} \propto \left[\frac{\rho_0}{\rho_j}\right] \cdot \left[\frac{U_j}{c_j}\right]^4 \cdot \left[\frac{c_j}{c_0}\right]^4 \cdot \left[\frac{4\pi}{\beta}\right] \cdot \left[\frac{d_e}{r}\right]^2 \cdot G_1\left(\frac{u_j}{c_j}, \frac{c_j}{c_0}, \theta\right) \cdot G_2(Kr)$$

$\beta$ is angle of radiation, $G_1$ is Directivity factor, $G_2$ is near field factor
1961 Limitations on Minimum Nozzle Size

Consider the nozzle discharge coefficient (actual mass flow divided by ideal)

- Figure 1 shows Reynolds number based on throat diameter
- Figure 3 is the basis for figure 1

Ref: Morgan, W. V., Sutherland, L. C., and Young, K. J., “The Use of Acoustic Scale Models for Investigating Near Field Noise of Jet and Rocket Engines,” WADD TR 61-178, Apr. 1961

1961 List of Vehicle Specific Acoustic Model Tests

Ref: Morgan, W. V., Sutherland, L. C., and Young, K. J., “The Use of Acoustic Scale Models for Investigating Near Field Noise of Jet and Rocket Engines,” WADD TR 61-178, Apr. 1961

Full Scale

- Minuteman (solid)
  - Silo
- Jupiter (Lox/ Kerosene)
  - Bucket deflector
- AR-1 Rocket (hydrogen peroxide/JP)
  - Horizontal firing

Model Scale

- 1/20 scale (solid) tethered (1 sec)
- 1/3 scale (solid) tethered (3 sec)
- 1/20 scale (cold flow) (30 sec)
- 1/36 scale
- 1/8 Scale (gox/ alcohol-water)
1961 Saturn I


- 1:20 Scale
- Model Saturn noise investigation measurement of simulated launch sound field
- MSFC Component Test Facility, cell 117
- Saturn cluster versus single F-1
- Water on deflector
- Spatial radiation characteristics of the source:
  - distribution of sound energy versus frequency
  - directivity patterns

VLF is Vehicle Launch Facility
Saturn IB Scale Model Acoustics

- Simulating an Edwards full scale test
- Horizontal and deflected configurations
- Ramps and vanes

Microphones
- At small angle increments for a 105° arc from deflected nozzle exhaust
- At 4 elevations along rocket
1962 624A Solid Propellant Booster


- 1:33 scale, Denver test stand D-1, 4 launch elevations
- Full and partial covered duct
  - Duct reduces noise
  - Increased duct length reduces noise
  - Max liftoff at 135' elevation
  - Duct width to encompass drift reduces noise
- Max levels are 5 to 12 decibels lower than with an open flame deflector
## 1964 Scaling Rocket Noise


### Table 1

**Assumed Engine Parameters and Computed Normalizing Factors**

<table>
<thead>
<tr>
<th>Missile/Model</th>
<th>Thrust $lbs \times 10^{-3}$</th>
<th>Mass $Wt.$</th>
<th>Number of Nozzles</th>
<th>Nozzle Dia. Ft</th>
<th>Eff. Nozz. Dia. D Ft</th>
<th>$\rho_j$ $lb/ft^3$</th>
<th>$k_a^{(1)}$ $db$</th>
<th>$k_f^{(2)}$ $ft$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atlas D</strong></td>
<td>352</td>
<td>14</td>
<td>3</td>
<td>2-3.8</td>
<td>5.5</td>
<td>0.00783</td>
<td>+2.8</td>
<td>5.64</td>
</tr>
<tr>
<td><strong>Jupiter</strong></td>
<td>185</td>
<td>6</td>
<td>1</td>
<td>4.08</td>
<td>0.00629</td>
<td>+4</td>
<td>4.06</td>
<td></td>
</tr>
<tr>
<td><strong>Minuteman</strong></td>
<td>181.8</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>3.94</td>
<td>+3.7</td>
<td>4.07</td>
</tr>
<tr>
<td><strong>1/3 Scale Min/Man</strong></td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.316</td>
<td>+3.2</td>
<td>1.41</td>
</tr>
<tr>
<td><strong>Saturn I</strong></td>
<td>1504</td>
<td>57</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+2.9</td>
<td>11.3</td>
</tr>
<tr>
<td><strong>Titan I Stg. I</strong></td>
<td>300</td>
<td>1192</td>
<td>8100</td>
<td></td>
<td></td>
<td></td>
<td>+2.5</td>
<td>5.02</td>
</tr>
<tr>
<td><strong>Titan I Stg. II</strong></td>
<td>67.3</td>
<td>256</td>
<td>8460</td>
<td></td>
<td></td>
<td></td>
<td>+4.5</td>
<td>2.63</td>
</tr>
<tr>
<td><strong>Titan II Stg. I</strong></td>
<td>430</td>
<td>1654</td>
<td>8370</td>
<td></td>
<td></td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Titan II Stg. II</strong></td>
<td>87.3</td>
<td>316.8</td>
<td>8870</td>
<td></td>
<td></td>
<td>2.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1/33 Scale Titan III</strong></td>
<td>1.1</td>
<td>4.92</td>
<td>7200</td>
<td>1</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ASD 1000#JATO</strong></td>
<td>1</td>
<td>4.47</td>
<td>7200</td>
<td>1</td>
<td>0.217</td>
<td>0.217</td>
<td>0.9168</td>
<td></td>
</tr>
<tr>
<td><strong>Augmented Thor</strong></td>
<td>329 $&lt; 170$</td>
<td>680</td>
<td>8060</td>
<td>1</td>
<td>3.81</td>
<td>3.43</td>
<td>0.009</td>
<td></td>
</tr>
</tbody>
</table>

1. Computed from Equation (13)
2. Computed from Equation (14)
1964 Scaling Rocket Noise: 1:33 Scale Titan III


- Scale model of the Titan III 120 in. solid rocket motor
- Due to large scale factor (33:1), used only to differentiate effect of long duct
- Later comparison with full scale data showed a favorable result
1964 Scaling Rocket Noise: 1:3 Scale Minuteman


- Scale acoustic model data measured for various points of vehicle emergence
- Full scale flight data taken as a missile flies out of silo in the form of maximum level in each 1/3 octave band
1966 Lox/H₂ Engine Clusters

- Horizontal firing: Nearfield & farfield
- One engine design, Multiple engine clusters
- Shift in major spectral peak to lower frequency with larger clusters

1967 S-1C and VLF-39

- Saturn V uprating test
- 1:58 Scale
- Test position 117A
- Heating rate and surface pressures
- five LOX/RP-1 pressure fed engines
- VLF-39 model
  - Flame trench
  - Flame deflector
  - LUT platform
  - Umbilical tower

*LUT is Launch Umbilical Tower*
Acoustic Model Test Facility (AMTF)

- Originally built for tests on Saturn models
- Modified in 1974 for Space Shuttle acoustic model testing
- 6.4% ETR and WTR Acoustic Model Test Programs were conducted at the AMTF
- Open steel test stand structure with a telescoping test article mount
- 180°, 75-meter blacktop area around the stand
- Used extensively in the 1970’s and 1980’s
- AMTF restored for testing in the 2010’s (Constellation & SLS)

*SLS is Space Launch System*
Test Description

• Shuttle model testing in 2 phases
  – MSFC test lab designed and built 6.4% scale SSME’s
  – Tomahawk used as 6.4% scale SRB
  – Phase I - Baseline acoustics and ignition overpressures
  – Phase II - Sound suppression
  – 153 firings

• Requirement for SPL 145 dB Orbiter payload bay internal
  – SSME and SRB contributions
  – Various elevations
  – Noise reduction designs studied
    • In the exhaust trench
    • In the exhaust holes
    • Above deck

Pad Design Outcome

Developed launch configuration that reduced Shuttle Liftoff Environments to meet payload bay acoustic requirements

• SRB trench side deflectors
• Elongated SRB hole
• SSME hole spray ring
• SRB trench side spray
• Main deflector crest spray
• Deck water spray (rainbirds)

SSV is Space Shuttle Vehicle
ETR is Eastern Test Range (Kennedy Space Center)
Space Shuttle 6.4% Scale Acoustic Model

1. SRB trench side deflectors
2. Elongated SRB hole
3. SSME hole spray ring
4. SRB trench side spray
5. Main deflector crest spray
6. Deck water spray (rainbirds)
1976 SSV WTR (P043)

- WTR is Western Test Range at Vandenberg Air Force Base
- 24 tests at MSFC TS-116 AMTF
- 6.4% scale SSV and WTR
- Plume deflector configurations
- Ignition overpressure and liftoff acoustics
- Various water injection schemes evaluated
- Four tests at elevation
1976 SSV WTR (P043)

Acoustic Model Testing
1977 SSV MPTA Model (P046)

- Subscale model of Stennis Space Center Main Propulsion Test Article (MPTA) and deflector
- Purpose was to test design and measure effectiveness of spray nozzles intended to reduce engine noise during Shuttle MPTA firing
1977 Titan III (P050)

- TS-116 AMTF
- 4 tests
- 7.5% Scale
Test Description

- Testing to design an overpressure suppression system to be installed at KSC
  - SRB ignition is source of overpressure therefore 6.4% scale SSME’s not needed
  - Tomahawk used as 6.4% scale SRB
  - 17 popper screening tests →
  - Baseline and suppression tests
  - 38 hot fire tests
  - Splitter plate employed to reduce number of Tomahawks needed
- Requirement to significantly reduce SRB IOP which caused unacceptable loads on orbiter elements during the 1st Space Shuttle Launch
- 6.4% scale model ignition overpressure achieved a knockdown of 5 to 8 from STS-1
Pad Design Outcome

1. Water filled hammocks across top of SRB hole (water bags)
2. North trench sidewall water disconnected
3. Water redirected into SRB primary exhaust hole at two elevations
Calendar, 6.4% Model, and KSC Water Systems

6.4% Scale Model Test Calendar

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETR Test Series Begin</td>
<td>Aug 1974</td>
</tr>
<tr>
<td>ETR Test Series End</td>
<td>Dec 1976</td>
</tr>
<tr>
<td>STS-1</td>
<td>Apr 12 1981</td>
</tr>
<tr>
<td>ETR 2nd Series Begin</td>
<td>Jul 1981</td>
</tr>
<tr>
<td>ETR 2nd Series End</td>
<td>Aug 1981</td>
</tr>
<tr>
<td>STS-2</td>
<td>Nov 12 1981</td>
</tr>
</tbody>
</table>

Rainbirds
(to reduce drift impingement acoustics)

SSME Water Ring
(to reduce exhaust plume acoustics)

SRB Water Injection
(to reduce ignition overpressure)
• 42 tests
• TS-116 AMTF
• 6.4% scale
1983 Aft Cargo Carrier (P085)

- 7 tests
- TS-116 AMTF
- 6.4% scale

- Aft Cargo Carrier proposed extension of Space Shuttle External Tank to provide additional cargo volume
- acoustic and overpressure data
- test was limited by available SRMs
1986 WTR Hydrogen Disposal (P216)

- 76 tests
- TS-116 AMTF
- 6.4% scale
- Acoustics of HDS configurations
  - J-deflector
  - Elbow deflector
  - Max slope deflector
  - Tiered deflector

HDS is Hydrogen Disposal System
1987 WTR Hydrogen Disposal (P216)

- Steam inerting, SLC-6
- Shuttle Assembly Building in forward parked position
- 6.4% scale steam in SSME duct
- Acoustic, overpressure, and thermal data

SLC is Space Launch Complex
1987 ETR Hydrogen Disposal (P225)

- 45 tests
- TS-116 AMTF
- 6.4% scale

Mass Spectroscopy

- Determine flame chemistry in time varying turbulent flow
- Use probes to sample flow
- ‘On line’ determination of chemistry
- Sample gas from water spray/steam mix
- Determine un-burned hydrogen and residual oxygen
1989 Titan IV (P238)

- 5.5% Scale Acoustics
- 63 tests
Ariane Scale Model Acoustic Testing

1999 Ariane V Scale Model Acoustic Test

- Used MARTEL facility for subscale testing
  - Cold and hot jets to simulate Ariane 5
  - Optimized water injection device at Kourou launch pad
  - Reduced noise radiated at liftoff compared to first flight


2000 Ariane

- 1:47 scale of SRB flue only
- Various flue lengths
- Extended to reduce fairing noise
- The absolute acoustic levels measured in MARTEL facility are not representative of the full scale but the relative levels between several test configurations can be extrapolated.
- Obtained 5 dB reduction

1999 – 2001 Linear Aerospike

- Multicell thruster and XRS-2200 static test to determine X-33 liftoff acoustics
  
  (X-33 is subscale RLV)

2001 Delta IV IOP and H2 OP

- Medium and Heavy configurations
- 1/7 scale RS-68
- Scaled geometry and time by 1/7
  - Full-scale velocity and pressures were matched
  - Sub-scale Cape configuration
- 1999 test at KSC
- 2001 test at Plum Brook
2004 Vega & ELA1 at MARTEL Facility


• 1:33 Scale ELA1 launch pad
  – Jet generator for Air-Hydrogen hot supersonic jets
  – Semi-anechoic room

• Cylindrical array with 12-free-field-microphones,
  – Spaced every 60° in azimuth and on two levels
  – Corresponds to fairing level of launch vehicle

• 1:20 Scale of VEGA and ELA1 Launch Pad
  – Facility support structure able to sustain the launcher at different altitudes during the static firing tests

• SRM designed to provide the same acoustic field generated at lift-off by the full scale Vega 1st stage SRM
  – Same Strouhal number as P80 full scale motor
  – 41 microphones distributed on vehicle
  – 6 microphones installed on launch pad elements
NTS Subscale Testing

• IOP studies
  – Titan 34D
  – Commercial Titan
  – Titan IV

• Launch acoustics
  – Atlas 2AS
  – Titan IV
  – Atlas V
2010 Ares Scale Model Acoustic Test (P8019)

- 1:20 scale of Ares I rocket
- RATO SRM
- On-deck water schemes
- IOP suppression schemes
- W/ and w/o launch mount

<table>
<thead>
<tr>
<th>Test</th>
<th>Elevation (ft)</th>
<th>Drift (in)</th>
<th>Launch Mount</th>
<th>Waterbags</th>
<th>Trench Water (gpm)</th>
<th>Exhaust Hole Water (gpm)</th>
<th>Rainbird (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>HORZ1</td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>873</td>
<td>291</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>VERT1</td>
<td>0</td>
<td>0</td>
<td>Yes</td>
<td>873</td>
<td>291</td>
<td>0</td>
</tr>
<tr>
<td>03</td>
<td>VERT2</td>
<td>0</td>
<td>0</td>
<td>Yes</td>
<td>873</td>
<td>291</td>
<td>0</td>
</tr>
<tr>
<td>04</td>
<td>VERT3</td>
<td>0</td>
<td>0</td>
<td>No</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>05</td>
<td>VERT4</td>
<td>2.5</td>
<td>4.625</td>
<td>Yes</td>
<td>873</td>
<td>291</td>
<td>0</td>
</tr>
<tr>
<td>06</td>
<td>VERT5</td>
<td>5</td>
<td>6.875</td>
<td>Yes</td>
<td>873</td>
<td>291</td>
<td>0</td>
</tr>
<tr>
<td>07</td>
<td>VERT6</td>
<td>7.5</td>
<td>8.375</td>
<td>Yes</td>
<td>873</td>
<td>291</td>
<td>0</td>
</tr>
<tr>
<td>08</td>
<td>VERT7</td>
<td>5</td>
<td>6.875</td>
<td>Yes</td>
<td>873</td>
<td>291</td>
<td>0</td>
</tr>
<tr>
<td>09</td>
<td>VERT8</td>
<td>5</td>
<td>6.875</td>
<td>Yes</td>
<td>873</td>
<td>291</td>
<td>566</td>
</tr>
<tr>
<td>10</td>
<td>VERT9</td>
<td>5</td>
<td>6.875</td>
<td>Yes</td>
<td>873</td>
<td>291</td>
<td>991</td>
</tr>
<tr>
<td>11</td>
<td>VERT10</td>
<td>5</td>
<td>6.875</td>
<td>No</td>
<td>873</td>
<td>175</td>
<td>991</td>
</tr>
<tr>
<td>12</td>
<td>VERT11</td>
<td>5</td>
<td>6.875</td>
<td>No</td>
<td>873</td>
<td>175</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>VERT12</td>
<td>5</td>
<td>6.875</td>
<td>No</td>
<td>873</td>
<td>175</td>
<td>1275</td>
</tr>
<tr>
<td>14</td>
<td>VERT13</td>
<td>5</td>
<td>0</td>
<td>No</td>
<td>873</td>
<td>175</td>
<td>991</td>
</tr>
<tr>
<td>15</td>
<td>VERT14</td>
<td>5</td>
<td>0</td>
<td>No</td>
<td>873</td>
<td>175</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>VERT15</td>
<td>5</td>
<td>9.875</td>
<td>No</td>
<td>873</td>
<td>175</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>VERT16</td>
<td>10</td>
<td>9.875</td>
<td>No</td>
<td>873</td>
<td>175</td>
<td>991</td>
</tr>
<tr>
<td>18</td>
<td>VERT17</td>
<td>5</td>
<td>0</td>
<td>No</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Major sound source at deflector. Correlation shows that acoustic environment is combination of diffuse and propagating field.
Provided acoustic environment in terms of R, β, and φ.
2015 Nozzle Flow Transient Acoustic Scale Model

- Launch duct geometry added later (2016)
- Designed to reproduce the same unsteady flow phenomenon as occurs on startup of RS-25 (SSME)
- Startup of 4 engines versus 3
- Acoustic env. on booster nozzle plug (relative to orbiter base heat shield)
Clues to Physical Processes

- Acoustics scales w/ Strouhal no. for frequency
- Amplitude scales with thrust
- Atmospheric attenuation
- Size limits to nozzle scaling
- Deflected noise is directional/ lobed
- As rocket elevation increases, noise spectrum peak shifts left
- Multiple nozzles have effective nozzle diameter
- Sound energy is proportional to the kinetic exhaust stream energy
- Self noise and Mach noise
- Noise doubling and Correlation aspects of liftoff noise
- Crackling requires high Mach number flow
- Non-linear spectral correlation at distance from max noise (sonic termination)
Summary

• Scale models first used to measure launch acoustics sensitivity to deflector and duct configurations
• Key scaling characteristics quickly realized
• Knowledge gained from generic acoustic models used to inform preliminary design
• Acoustic models eventually used to predict launch acoustics
• Multitude of tests gave insight to physical processes for noise production and propagation
• Acoustic models used for other launch environments, e.g., ignition overpressure, hydrogen pop, debris transport model validation, etc.
• Vibroacoustic community has need for improved characterization of the acoustic field generated by the propulsion system
  – Ratio of diffuse to propagating field, $R$
  – Decay coefficient, $\beta$
  – Angle of incidence, $\phi$
State of the Practice

- Detailed modeling and simulation is now part of the launch acoustic environment definition process
  - Solid motor internal ballistics
  - Transient nozzle exhaust flow (liquids and solids)
  - 3-D HRLES plume
  - 3-D DGS for nonlinear CAA
  - Water spray systems
  - DTA
- Validation via scale models and full scale launches
- Provides high fidelity insight
  - To interpret scale model results
  - To assess launch pad design details/ modifications