Frequency-Based Spatial Correlation Assessments of the Ares I Subscale Acoustic Model Test Firings

164th Acoustical Society of America Meeting
Noise, Physical Acoustics, Structural Acoustics, and Vibration:
Launch Vehicle Acoustics
Session 3aNS
October 24th, 2012
SLS Liftoff Acoustics – Spatial Definition

- Launch vehicle liftoff acoustic environment defined by multiple sound sources and time-dependent vehicle / launch pad geometric relationships.

- Liftoff environment definition needed by vibration analysts to determine accurate hardware responses.

- Space Launch System (SLS) program vibration analysts have requested that the SLS liftoff acoustics environments include:
  - Vehicle zone dependent acoustic spectra for entire liftoff timeframe
  - Vehicle zone dependent acoustic spatial definition for entire liftoff timeframe

- Spatial definition of fluctuating pressure environments are needed to better determine hardware responses to a given acoustic spectra.
  - General process previously shown by Prock et al. “Recovering the Spatial Correlation of Liftoff Acoustics from the Ares I Scale Model Acoustics Test” (ASA-2011)

- This presentation will review efforts by MSFC to establish a more rigorous process for acoustic spatial definitions for use in official SLS analyses.
  - Ares I Scale Model Acoustics Test (ASMAT) data being leveraged to develop process
What field type does rocket / liftoff noise produce?
- SP-8072 models assume point sources -> propagating?
- But, multiple sources exist at a given frequency and cross-interfere -> diffusive?

SLS acoustic environment classified as a mixture of two field types per frequency band:
- Diffuse field – uniform acoustic energy from all directions referenced to a given evaluation point
  - Acoustic spectra
- Propagating field – acoustic energy from a particular orientation referenced to a given evaluation point
  - Acoustic spectra
  - Angle of incidence (or trace velocity)
  - Decay coefficient
    - Geometric decay (planar, cylindrical, or spherical?)
    - Absorption coefficient

MSFC needs to identify a process to define the mixed field parameters
- Will use spatial correlation plates on upcoming Scale Model Acoustic Test (SMAT)
Empirical Identification of Spatial Characteristics

- Traditional approaches use an acoustic pressure measurement pair to characterize the cross-spectral relationships ('spatial correlation') between individual locations ('x' and 'y') within the acoustic field
  - Measurement pairs located 'close' to each other and to other measurement pairs to increase fitted parameter confidence -> multiple measurement pairs mounted on spatial correlation 'plate'
  - Referenced in Bendat & Piersol: *Engineering Applications of Correlation and Spectral Analysis*

- Linear coherence between locations ('x' and 'y')

\[
|\gamma_{xy}(f)| = \left( \frac{r_x}{r_x + d_{xy}} \right)^{n_{xy}} e^{-\alpha_{xy} d_{xy} \cos \phi} \right) \left( 1 + R \right) \left( \left( \frac{r_x}{r_x + d_{xy}} \right)^{n_{xy}} e^{-\alpha_{xy} d_{xy} \cos \phi} \right)^2 + R
\]

- Relative phase between locations ('x' and 'y')

\[
\theta_{xy}(f) = 2\pi f \tau_{xy} = \frac{2\pi f d \cos \phi}{c}
\]
ASMAT had spatial correlation (SC) plates distributed throughout the vehicle body
  - Five pressure sensors per mounting plate
  - Spacing ranged from 0.5” to 4.5” apart
  - Phase synchronized specifically for spatial correlation assessments
  - Use linear coherence and relative phase relationships to determine SC parameters

Leverage ASMAT SC data to develop SLS / SMAT SC process
ASMAT SC Plate Parameter: Fitting Procedure

♦ ASMAT program had 14 tests with SC plates installed (tests #4 - #17)
♦ For each spatial correlation plate installed, six sets of linear coherence and relative phase spectra were calculated per test
  • Analysis window corresponds to established steady-state firing times of test
  • Frequency bandwidth was ~ 15 Hz, and number of averages was 55
  • Spectra was fit over 400 – 40,000 Hz model scale (~ 20 – 2000 Hz full scale)
♦ Six sets of relative phase spectra were fit to determine average incident angle referenced to vehicle vertical axis
  • Metrics determined where incidence angle was independent of frequency (propagating) and where values were non-viable (diffuse)
♦ Six sets of linear coherence spectra were fit, versus frequency, to determine:
  • $R$
  • $n$
  • $\alpha_{\text{vert}}$
  • $\alpha_{\text{azimuthal}}$
♦ Data results shown in next several slides:
  • Average $\phi$ for vehicle zone locations and SC plate location for a given zone
  • Maximum $n$ and $R$ values seen over all frequency, for each SC plated and each test
  • $R$ values seen versus frequency for multiple selected tests
  • $\alpha_{\text{vert}}$ values versus frequency for multiple selected tests
Zone 1 shows most interesting variations test to test

Higher zones all show evidence of propagating wave field coming nearly parallel to vehicle vertical axis
Zone 1 shows most interesting variations test to test
Higher zones all show evidence of significant propagating wave field component with spherical geometric decay
No significant effects of elevation; tower side has more diffuse field content
No significant effects of water; tower side has more diffuse field content.
Acoustic Field Parameter: Zone 1 $\alpha_{\text{vert}}$ Spectra Model Elevation Comparisons

- Relatively constant levels over frequency; higher than atmospheric absorption
Acoustic Field Parameter: Zone 1 $\alpha_{\text{vert}}$ Spectra

Model Water Effect Comparisons

- Water appears to increase decay values on tower side

---

Rainbird Water

Below Deck Water: ML

Below Deck Water: Trench
Conclusions and Forward Work

- **MSFC improving how ‘design-to’ acoustic environments are defined**
  - Inclusive of spatial correlation information to aid in refined vibroacoustic measurements

- **SLS acoustic model testing will include spatial correlation plates**
  - Number of sensors per plate = 5 – 7
  - Placed multiple areas along vehicle

- **ASMAT spatial correlation data used to help develop acoustic environment definition process**
  - Good measurements and variety help with refining approach

- **Results show that mixed field considerations are needed for aft skirt region, but less so for higher zones**
  - Important to define spatial parameters versus frequency to better capture range of possibilities.

- **Parameters show frequency dependency, but not much sensitivity on launch vehicle configuration**
  - Propagating wave field appears to be spherically spreading
  - Diffuse field content increases with frequency for aft skirt zone
  - Linear absorption decay values much higher than predicted by solely atmospheric absorption
    - Need to refine fitting process!

- **Will continue to refine parameter determination to prepare for SMAT testing results**
  - Scaling – more geometric parameters identified, the better
  - Dispersions – will use Monte Carlo approach to identify uncertainties
    - More sensor pairs will decrease uncertainty
BACKUP
ASMAT Coordinate System
The propagating wave definition for the fluctuating pressure is:

\[ p_p(r, t) = \left( \frac{r_o}{|r|} \right)^n P_o e^{-\alpha n \cdot r} e^{i(k \cdot r - \omega t)} \]

where:
- \( r \) = distance vector from the source center
- \( r_o \) = source radius
- \( P_o \) = source emitted pressure
- \( \alpha \) = linear attenuation coefficient
- \( k \) = wavenumber vector
- \( n \) = geometric spreading coefficient
  - \( n = 0 \): plane wave
  - \( n = 0.5 \): cylindrical wave
  - \( n = 1 \): spherical wave
The mixed acoustic field definition for the autospectral density is the summation of the diffuse field and propagating field contributions for a given frequency:

\[ G(\omega) = G_p(\omega) + G_d(\omega) = G_p(\omega)(1 + R) \]

where:
- \( G \) = autospectral density at frequency \( \omega \)
- \( R \) = ratio of diffuse to propagating field autospectral densities

\( G(\omega) \) can be substituted into the sound pressure level definition to see the effect of \( R \) on relative decibel levels (\( SPL \))

\[ SPL(\omega) = SPL_p(\omega) + 10 \log(1 + \frac{R_{\text{diffuse}}}{R_{\text{propagating}}}) \]

Diffuse field contribution at \( \omega \)

Total sound pressure level at \( \omega \)

Propagating sound pressure level at \( \omega \)
Sound Pressure Level Dependence on R

![Graph showing the dependency of sound pressure level on R. The graph plots Sound Pressure Level (dB) on the y-axis against R on the x-axis. The data shows an increasing trend as R increases.]
The propagating field, \( G_p(f) \), has defined cross-spectral properties measured between two locations ('x' and 'y') within the field:

- **Cross-spectrum**

\[
G_{xy}(f) = G_p(f) \left( \frac{r_x}{r_y} \right)^{n_{xy}} e^{-\alpha_{xy}d \cos \phi} e^{-i2\pi f \tau_{xy}} + G_d(f) \frac{\sin(2\pi fd/c)}{2\pi fd/c}
\]

- **Linear coherence**

\[
|\gamma_{xy}(f)| = \left( \frac{r_x}{r_x + d} \right)^{n_{xy}} e^{-\alpha_{xy}d \cos \phi} \sqrt{1 + R \left( \left( \frac{r_x}{r_x + d} \right)^{n_{xy}} e^{-\alpha_{xy}d \cos \phi} \right)^2 + R}
\]

- **Relative phase**

\[
\theta_{xy}(f) = 2\pi f \tau_{xy} = \frac{2\pi fd \cos \phi}{c}
\]
The diffuse field, $G_d(f)$, has defined cross-spectral properties measured between two locations (‘x’ and ‘y’) within the diffuse field:

- **Cross-spectrum**

$$G_{d\_xy}(f) = G_d(f) \frac{\sin(2\pi fd/c)}{2\pi fd/c}$$

- **Linear coherence**

$$|\gamma_{d\_xy}(f)| = \left| \frac{\sin(2\pi fd/c)}{2\pi fd/c} \right|$$

- **Relative phase**

$$\theta_{d\_xy}(f) = 0$$

- where:
  - $d =$ distance between locations
  - $c =$ ambient sound speed
The propagating field, $G_p(f)$, has defined cross-spectral properties measured between two locations (‘x’ and ‘y’) within the field:

- **Cross-spectrum**

$$G_{p_{xy}}(f) = G_p(f) \left( \frac{r_x}{r_y} \right)^{n_{xy}} e^{-\alpha_{xy} d \cos \phi} e^{-i2\pi f \tau_{xy}}$$

- **Linear coherence**

$$|\gamma_{p_{xy}}(f)| = 1$$

- **Relative phase**

$$\theta_{d_{xy}}(f) = 2\pi f \tau_{xy} = \frac{2\pi f d \cos \phi}{c}$$

- **where:**
  - $\phi$ = incidence angle
  - $r_i$ = distance from source to measurement location ‘i’
  - $n_{xy}$ = geometric decay coefficient ($n = 0$; plane wave, $n = 1$; spherical wave)
  - $\alpha_{xy}$ = absorption decay coefficient
Higher elevations show more diffuse field content on tower side
No significant effects of water

- **Below Deck Water: Trench**
- **Below Deck Water: ML**
- **Rainbird Water**
Acoustic Field Parameter: Zone 9 $\alpha_{\text{vert}}$ Spectra
Model Elevation Comparisons

- Relatively constant levels over frequency; higher than atmospheric absorption
Acoustic Field Parameter: Zone 9 $\alpha_{vert}$ Spectra

Model Water Effect Comparisons

No real differences between levels