Comparison of sonic boom propagation and loudness level calculations

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Introduction

- Elements of sonic boom propagation
- Sonic boom propagation prediction and metrics calculation tools are used to evaluate supersonic aircraft designs
- Desire to compare predictions from different developers
Previous Study

• Comparison of sonic boom propagation codes conducted by Cleveland et al.
  – Three codes compared favorably

![Graph showing overpressure (Pa) vs. time (ms) for different codes: THOR, SHOCKN, Weak shock theory, and ZEPHYRUS.]

• Reasons to conduct a new comparison
  – Codes have been modified over last 20 years
  – New codes have been developed
  – Boom waveforms of interest have changed
  – Cleveland analysis did not consider any noise metrics

Sonic Boom Propagation and PL Comparison

Objective
– To achieve more consistent results across partners and to facilitate understanding of possible differences in computer codes used in sonic boom research

Approach
– Conducted a new baseline comparison of sonic boom atmospheric propagation and noise metric calculation tools
  • Developed a set of input cases for propagation and Perceived Level (PL) calculation
  • Participating organizations used their tools to run these cases and returned their results to NASA
  • All provided results were reviewed and compared with baseline results from NASA’s tool suite
Summary of Perceived Level (PL)

- Metric for perceived level of loudness developed by Stevens
  - Developed to predict behavior of human auditory system in response to sound
- Adapted for use with sonic booms by Shepherd and Sullivan
- PL has been shown to correlate well with human perception of sonic booms heard outdoors
  - PL is used today to evaluate supersonic aircraft designs

- Uses signal spectrum in one-third-octave bands
- Uses a set of frequency weighting contours that vary with level
  - (By contrast, A-weighting contour does not vary with level)
  - Based on equal loudness contours for bands of noise
  - Extends down to 1 Hz, but this is an approximation
- Band of highest weighted level is the most important to overall level

Calculation Steps for Perceived Level (PL)

1. Calculate Sound Pressure Level of signal in 1/3-octave bands
2. Apply frequency weighting for loudness of individual bands
   - where loudness of 1 sone is referenced to 1/3-oct band of noise at 3150 Hz at 32 dB
3. Apply summation rule for total loudness
   \[ S_t = S_m + F(\Sigma S - S_m) \]
   where
   \( S_t \) = total loudness
   \( S_m \) = loudness of loudest band
   \( \Sigma S \) = sum of loudnesses of all the bands
   \( F \) = fractional factor based on \( S_m \)
4. Convert to PL in dB
   \[ PL = 32 + 9 \log_2(S_t) \]

PL Test Cases of Ground Booms

- Included to test that PL algorithms are implemented correctly
- Synthesized N-waves with different rise times, peak pressures, and durations
- Adequately sampled at 48 kHz with ample zero-padding
- Initial results indicated some codes needed to be modified to be in compliance with NASA’s baseline method
- Majority of updated results within 0.1 dB of baseline (all within 0.45 dB of baseline)
PL Test Cases of Ground Booms

- Included to highlight difficulties in processing measured booms and predicted booms
- Results more varied than for simpler cases
- Windowing, zeropadding, and resampling methods varied
- All calculations agree within 1 dB of baseline
Sonic Boom Propagation Prediction Overview

- Input is the overpressure signature predicted at several body lengths away from the aircraft

- Geometrical acoustics method (ray tracing)
  - Determines propagation path from altitude to ground
  - Accounts for variations in speed of sound and wind speed

- Nonlinear, lossy propagation based on extended generalized Burgers equation
  - Predict evolution of sonic boom as it propagates along rays
  - Second-order nonlinearity and the formation of shocks
  - Atmospheric absorption due to thermoviscous and molecular relaxation effects
    - Varies according to input of atmospheric conditions (stratified atmosphere)
  - Geometrical spreading loss
  - Solved numerically with a finite-difference method

- Numerical implementation varies
Inputs to Propagation Codes

- Overpressure signature predicted at several body lengths away from the aircraft
  - F-function
  - Overpressure distribution on a cylindrical surface from CFD flow predictions
  - Wind tunnel test measurement
  - In-flight near-field probing measurement

- Flight altitude and Mach number

- Flight trajectory

- Atmospheric conditions
  - Atmospheric pressure, temperature, relative humidity, winds

- Ground impedance or reflection factor
Propagation Test Cases

- Near-field signature, Mach number, altitude, and atmospheric conditions provided as input to sonic boom propagation codes
- Ground waveforms (undertrack) requested as output
- PL calculated with NASA baseline tool
- Boom 5: multi-shock low-boom configuration
- Boom 6: strong front shock

![Boom 5 Graph](image1)

**Boom 5**
Mach 1.6
13,700 m

![Boom 6 Graph](image2)

**Boom 6**
Mach 1.6
14,630 m
Atmospheric Conditions

- No winds included
- Temperature and relative humidity provided
  - Boom 5 conditions are similar to U.S. Standard Atmosphere (1976) and ANSI S1.26-1995 App. C (2009)
  - Boom 6 conditions are non-standard and include unrealistic relative humidity values
Initial Results for Propagation Test Cases

- Boom 5 results within 0.7 dB of baseline
- Boom 6 results varied by up to 10 dB from baseline
- Main variation across partners due to differences in mid-frequency content
- In addition to method differences, differences in PL may be due to assumptions and input settings of
  - Vehicle length
  - Atmospheric pressure
  - Sampling frequency
  - Step size

Examined using NASA baseline tool sBOOM

Effect of Sampling Frequency (sBOOM)

- Variations observed of 0.4-0.7 dB
- Convergence
  - Boom 5 sampling frequency = 697 kHz
  - Boom 6 sampling frequency = 462 kHz
- Sampling frequency/number of points needed depends on input waveform
  - Higher sampling frequency needed to resolve fine shock structure
Effect of Step Size (sBOOM)

- Variations observed of ~ 0.5 dB
- Boom 5 and 6 convergence at $10^{-5}$ step size
- Step size needed depends on input waveform
- Computation time varies from 10-20 s for $10^{-3}$ to ~22 hours for $10^{-6}$

![Graphs showing PL (dB) vs Step Size for Boom 5 and Boom 6]
2nd Round: Revised Atmospheric Conditions

- Revised atmospheric conditions for Boom 6
  - More resolution in relative humidity definition
  - Specified atmospheric pressure due to suspected differences in built-in calculation of pressure in different codes
- Updated Boom 6 results are within 3.5 dB of baseline
Revised Results for Propagation Test Cases

### Boom 5

![Graph showing pressure and time for Boom 5]

- **Time (s)**: -0.05 to 0.1
- **Pressure (Pa)**: -15 to 15

### Boom 6

![Graph showing pressure and time for Boom 6]

- **Time (s)**: -0.05 to 0.25
- **Pressure (Pa)**: -50 to 100

### NASA Baseline PL = 75.95 dB

- **A. PL = 75.86 dB**
- **B. PL = 75.81 dB**
- **C. PL = 75.47 dB**
- **D. PL = 75.50 dB**
- **E. PL = 75.28 dB**
- **F. PL = 75.78 dB**

### NASA Baseline PL = 98.86 dB

- **A. PL = 98.72 dB**
- **B. PL = 98.29 dB**
- **C. PL = 98.30 dB**
- **D. PL = 100.78 dB**
- **E. PL = 95.37 dB**
Loudness for Propagation Test Cases

Boom 5

NASA Baseline PL = 75.95 dB
A. PL = 75.86 dB
B. PL = 75.81 dB
C. PL = 75.47 dB
D. PL = 75.50 dB
E. PL = 75.28 dB
F. PL = 75.78 dB

Boom 6

NASA Baseline PL = 98.86 dB
A. PL = 98.72 dB
B. PL = 98.29 dB
C. PL = 98.30 dB
D. PL = 100.78 dB
E. PL = 95.37 dB
Summary

• Comparison of PL calculations and boom propagation predictions for 6 test cases resulted in
  – Some modifications of codes for consistent implementation
  – Awareness of factors contributing to differences
    • Observed up to 3.5 dB variation due to propagation codes
    • Observed less than 1 dB variation due to sampling frequency and step size
    •Observed up to 1 dB variation due to ground signal processing

• Majority of submissions in very good agreement with baseline
  – Differences at high frequencies generally occur at very low levels that are not significant to PL or human response

• Based on these results, baseline calculation recommendations have been drafted for ease of evaluation of supersonic aircraft designs

• Future
  – Could be useful to consider the effect of winds in different codes
  – Include more participants
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Baseline Boom Propagation Prediction Method

- Sonic boom propagation prediction
  - sBOOM is the preferred tool, and it is available from NASA
  - A standard atmosphere should be used (U.S. Standard Atmosphere, 1976):
    - Pressure, temperature, and humidity
    - No winds should be included
- sBOOM should be used for all boom predictions, with the exception of focus boom predictions. Since sBOOM does not include calculation of focus booms, other methods may be used.
- The step size should be set to 0.001
- The sampling frequency should be set to \( \geq 40 \text{ kHz} \) i.e. do NOT use resamp.dat from sBOOM output to calculate loudness metrics
- Propagation should start at a distance from the aircraft that gives a converged ground signature
- The ground reflection factor should be set to 1.9
- Sufficient zeropadding should be applied to the input waveform to avoid clipping the shocks during propagation
Baseline PL Calculation Method

- LCASB is the preferred tool, and it is available from NASA
- PL should be calculated according to Shepherd and Sullivan (1991)
- PL should be calculated on the waveform with a sampling frequency $\geq 40$ kHz
- A Hanning-type window should be applied to the beginning and ending of the waveform to ensure a smooth transition to zero acoustic pressure. This window should be applied so as not to affect the main boom event to be analyzed.
- Adequate zeropadding should be applied to allow for resolution of low frequencies (total signal length $\geq 0.5$ s)
- PL values should be rounded to the nearest 0.1 dB