MACH CUTOFF ANALYSIS AND RESULTS FROM NASA’S FARFIELD INVESTIGATION OF NO-BOOM THRESHOLDS

22\textsuperscript{nd} AIAA/CEAS Aeroacoustics Conference
Lyon, France
June 1, 2016

Presented by:
Larry J. Cliatt, II

Authors:
Larry J. Cliatt II, Michael A. Hill, Edward A. Haering, Jr.

\textit{NASA Armstrong Flight Research Center}
FARFIELD INVESTIGATION OF NO-BOOM THRESHOLDS (FAINT)
Aeronautics Flight Research

- Over 60 years of flight research (NACA Muroc Flight Test Unit)
- Edwards Air Force Base (EAFB)
- Remote Location
- 350 Testable Days Per Year
- Extensive Range Airspace
- Supersonic Corridor
TOPICS OF DISCUSSION

• Motivation & Objectives
• Test Setup
• Flight Profile Planning
• Analysis
  – Mach cutoff calculations
  – Metrics for Mach cutoff acoustics
  – Noise levels due to Mach cutoff
  – Sensitivity Analysis
• Summary & Considerations
**Motivation & Background**

• What is Mach Cutoff flight?
  – Supersonic flight when sonic boom rays do not reach the ground
  – Rays refract due mostly to temperature gradient

• Commercial implications
  – “Boomless” flight
  – Speeds up to Mach 1.3
  – Increase in operations by over 30%
• **Need:** Understanding of entire sonic boom envelope
  
  • Change in ICAO/FAA regulations
  
  • Notable noise due to Mach cutoff flight ($M_{CO}$)
  
  • Inconclusive results from previous tests
  
  • Limitations to common numerical predictions:
    – Based on geometrical acoustics
    – No solutions in shadow zones
PRIMARY OBJECTIVES

• Study evanescent wave field
  – Finely spaced measurements
  – Attenuation and increase in signature length
  – Evanescent decay in shadow zone

• Design tools for flight planning and post-flight analysis

• Develop noise–$M_{CO}$ relationship

• Build database
FLIGHT PROFILE PLANNING

• Goal: Produce a range of cutoff altitudes ($Z_{CO}$) between 2500 – 8000 ft (762.0 – 2438.4 m)
  – Assume initial flight altitude ($Z$) and heading
  – Calculate required Mach ($M$)

• Rays refract above ground when their propagation speed ($V_p$) exceeds the airplane ground speed ($V_G$):

$$\frac{V_p}{V_G} \geq 1.0$$

$$V_G = Ma_0 - u_{n0} \quad (1)$$

where

$$V_P = \{a(Z) - u_n(Z)\} \quad (2)$$

- $a$: speed of sound
- $u_n$: wind speed direction of propagation
- 0: subscript denotes at flight altitude

• Because $V_p$ increases toward the ground:

$$Z_{CO} = Z \ @ \ \max \{V_P \geq V_G\} \quad (3)$$

• Use Eq. 1 to compute M that satisfies Eq. 3
TEST SETUP

• Flight Conditions
  – F-18B airplane
  – Mach 1.128 – 1.174 and 34400 – 39300 ft (10.5 – 12.0 km) pressure altitude

• 7375 ft (2.2 km), 125 ft (38 m) spaced linear microphone array at 2300 ft (0.7 km) mean sea level
  – 60 microphones

• PCBoom\(^1\) used for initial flight planning

\(^1\) PCBoom was developed by Wyle (El Segundo, California)
• Mach threshold \((M_T)\): Fastest Mach for \(M_{CO}\)
• \(M_T\) is independent of \(Z_{CO}\)
• Dependent only on atmospheric conditions, mostly \(V_{P,max}\)

\[
M_T = \frac{1}{a_0} \left[ V_{P,max} + u_n \right]
\]
 Metrics for Mach Cutoff Acoustics

- Overpressure alone not sufficient for sonic boom analysis
- Familiar metrics less applicable for waveforms near lateral cutoff and beneath Mach cutoff altitude due to variable duration and impulsiveness
- **Perceived Sound Exposure Level (PL$_{SEL}$)**
  - 99% energy windowing
  - Sound Exposure Level (SEL) 1-second normalized integration (ISO 1996)
  - Stevens’ Mark VII Perceived Level weighting
- New parameter: \((M_T - M)\)
  - Relates \(Z_{CO}\) to Mach number
  - More natural to commercial piloting operations

- However, correlation between \((M_T - M)\) and noise on the ground \((PL_{SEL})\) is indistinct due to varying \(Z_{CO}\)
- Correlation between $Z_{CO}$ and $PL_{SEL}$ is also indistinct
- Possibly due to sonic boom shock strength (Mach number)
• “Normalize” by $Z_{CO}$

• First known empirical model for shadow zone acoustics: 
  \[ PL_{SEL} = f(M_T - M, Z_{CO}) \]

• Exponential decay fit $\rightarrow$ evanescent wave field
**SENSITIVITY ANALYSIS**

- Monte Carlo simulation of 5000 $M_{CO}$ cases
  - Constant Mach (1.135) and altitude 37000 ft ($11277.6$ m)
  - Random normal distribution of: wind speed ($\sigma = 3$ knots), wind direction ($\sigma = 10$ deg), and temperature ($\sigma = 3$ °C)
- “Banding” of $Z_{CO}$ due to “effective $V_p$”

Red bars are as-flown values
SUMMARY & CONSIDERATIONS

- $PL_{SEL}$ shown to be a more consistent and applicable metric Mach cutoff sonic boom acoustics
- First known empirical model of Mach cutoff shadow zone acoustics allows:
  - The ability to predict sonic boom noise levels in real-time
  - Capability to design supersonic commercial airplane mission profiles for entire flight regime
  - Fast analysis. Computational models require significant computer core hours
- $M_{CO}$ is extremely sensitive to atmospheric changes
  - Commercial applications will require sophisticated flight planning tools
• Larger database to refine empirical model
• Verification of empirical model during flight
• Use model to validate computational codes, such as Gulfstream’s Lossy Nonlinear Tricomi Equation (LNTE)
• Beamforming analysis (Boeing)
THANK YOU.
MACH CUTOFF CALCULATIONS, cont.

- Importance of accurate windowing
SENSITIVITY ANALYSIS, cont.

• Changes in both atmosphere and flight parameters