Fixing the Sound Barrier

Three Generations of U.S. Research into Sonic Boom Reduction

... and what it means to the future

Presented at the FAA Public Meeting on Sonic Boom

July 14, 2011
Outline

• Perspective
  – Concorde & The U.S. SST
  – Recent interest in supersonic civil aircraft

• Sonic boom basics

• Progress in Sonic Boom Minimization

• What’s happening now

• Looking forward
Perspective

Concorde

- Cruise Speed: Mach 2
- Takeoff Weight: 400,000 lbs
- Payload: 100 passengers
- First Flight: 1969
- Commercial Service: 1976-2004

U.S. SST

- Cruise Speed: Mach 2.7
- Takeoff Weight: 675,000 lbs
- Payload: 274 passengers
- Program Start: 1965
- Program Cancelled: 1971
Perspective

Concorde, U.S. SST faced many challenges

...Leading to the FAR prohibiting supersonic commercial flight over U.S.

One of the largest was... SONIC BOOM!
Interest in Supersonic Flight has not Diminished

Supersonic cruise aircraft offer significant mobility improvements in the Future Air Transportation System

Supersonic flight over land will enable a revolution in transportation …

… up to 50% reduction in cross country travel time

… improving personal productivity and well-being

… moving time-critical cargo, including life-saving medical supplies

… enhancing homeland security through rapid transportation of critical responder teams

Supersonic Civil Aircraft with increasing capability will be enabled if technology and environmental barriers can be overcome
Sonic Boom Basics

• Speed < Speed of Sound (< Mach 1)
• Pressure Disturbance (sound) precedes aircraft

• Speed = Speed of Sound = Mach 1
• Aircraft Speed = Speed of Pressure Disturbance

• Speed > Speed of Sound > Mach 1
• Aircraft precedes pressure disturbance
• All disturbance reaches an observer instantaneously

_Sonic Boom is NOT the sound of an aircraft “breaking the sound barrier”_
_Sonic Boom is created as long as the aircraft is flying faster than Mach 1.0_
Sonic Boom Basics

- Sonic Boom is 3-Dimensional
- Large “Carpet” of ground is exposed as aircraft flies
- Noise is reduced at the edge of the carpet

Multiple disturbances ("shock waves") near aircraft

- Disturbances Merge
- Signal lengthens
- Noise attenuates

- Two disturbances remain
- Signal has a characteristic “N” shape
- Called an “N wave” boom “signature”
Sonic Boom Basics: The N-Wave

Measured Sonic Boom

To the same scale

Measured Subsonic Overpressure
Takeoff Flyover

ΔP

Time, s

0 10 20 30 40 50 60

0 0.1 0.2

Duration

Rise Time

Factors in N wave annoyance

Time, s

0 10 20 30 40 50 60

-0.2 -0.1 0 0.1 0.2

-0.2 -0.1 0 0.1 0.2
Sonic Boom Research in Supersonic R&D Programs

1st Generation
60’s-70’s Concorde U.S. SST
Mach: 2.0 -2.7
TOGW 400,000 - 675,000 lbs
Payload: 100 -234 Passengers
Sonic Boom Basics
Community Impact
Shaping Concepts

2nd Generation
80-90’s High-Speed Research
Mach: 2.4
TOGW 750,000 lbs
Payload: 300 Passengers
Shaping Benefit
Low Boom Design
Community & Wildlife Impact

3rd Generation
Current Efforts NASA, FAA & Industry
Mach: 1.2-2.0
TOGW 100,000- 300,000 lbs
Payload: 8-100 Passengers
Integration of Low Boom Design
Indoor Noise Impact
Atmosphere Effects

DARPA Quiet Supersonic Platform
Mach: 2.4
TOGW 100,000 lbs
Payload: 20,000 lbs
Benefit of Small Size
Low Boom Design
Flight Validation of Boom Shaping

We are doing something!

Can we do something?

Can we live with it?
If Aircraft ground speed < Speed of Sound at the ground (~760 mph)…

Boom can “refract” and not reach the ground

"Caustic Line"

Rumble sound, rapidly decaying
Practical Approaches to Sonic Boom Reduction - 2
Minimization Through Aircraft Shaping

Shocks Coalesce into “N-wave”

Disturbances do not Fully Merge

Control Strength and Position of Disturbances

Shaped Boom at the Ground

Minimum Overpressure

Minimum Initial Shock
Noise Reduction from Sonic Boom Shaping

A = 1.3 psf

Rise Time

Mean Loudness Rating

Sullivan 1990
Practical Application of Boom Shaping Concept

**George & Seebass 1969**

**Area Distribution**

**F-Function**

**Ground Signature**

**Darden and Mack, 1979**

Minimizing Program

Design Conditions
- Weight, Wc
- Mach No., M
- Altitude, h
- Nose Length, \( \lambda_{te} \)
- Total Length, \( t_e \)

Minimum Noise Shock Option

Minimum Overpressure Option

Total of Volume and Lift Equivalent Areas

\[ \frac{A_e}{2} \]

Volume and Lift

Volume
Experimental Validation of Boom Reduction Concepts

- Scale model tests in supersonic wind tunnels
Key Step in Validation of Theory

Demonstrate Shaped Boom Propagation in Real Atmosphere…

… Through Ground Measurement of Booms from Modified and Unmodified F-5Es

Shock Thickening Adjusted Ground Boom Signature Comparisons
Shaped Sonic Boom Demonstrator (SSBD)

F5-E loaned by US Navy

Wind tunnel validation of design

Extensive design effort using most up to date computational methods

Engineering, fabrication & flight clearance for research aircraft
Theory Validated!

First-Ever Shaped Sonic Boom Recorded 27 August 2003

Signatures recorded during SSBD back-to-back data flights in the Edwards AFB supersonic flight corridor early morning.

Flight conditions:
Mach 1.36+, Altitude 32,000 ft

Design Mach: 1.4
Impact of Boom Shaping on Noise

Low Boom signatures are achieved by applying shaping to smaller aircraft.

Potentially more than 35 dB(a) of Reduction!

~2000x less sound intensity
Research on Boom Acceptability
How do We Determine What is Low Enough?

- Sophisticated boom simulators
- Greatly improved reproduction of sonic boom noise
  - Consistent, repeatable test conditions
- Study elements of boom that create annoyance
  - Goal: Understand how annoyance is related to spectrum, level, rattle, vibration
How do We Study Low Sonic Boom?

- Current aircraft cannot generate low booms during straight and level flight
- Sonic boom is generated during supersonic dive of an F/A 18 aircraft
- Long propagation distance, significant attenuation
- Boom amplitude observed at house is adjusted by moving dive location relative to the house

Boom Amplitude .1-.5 PSF (5-25 Pa)
Boom Loudness 60-80 PLdB

10 to 20 miles
Research in Realistic Environments

- Dive maneuver creates new research opportunities
- Realistic, varied structures and environments
  - Living & working conditions
- Test conducted in approved supersonic flight corridors

Structural & Acoustic Response

Subjective Reaction

Small & Large Structures
Flight Validation is a Critical Next Step

- Full scale, complete validation of design tools & techniques
- Develop understanding of the full spectrum of atmospheric effects
- Validate acceptability measures in realistic situations
- Gather data on public reaction to low noise sonic boom
  - Communities without prior experience of sonic boom exposure

Gulfstream Clean Sheet Design

Boeing F-16XL Based Design
Summary of Sonic Boom Research

Past Research

- Basics of sonic boom creation, propagation and impact are well understood
  - Effects on structures, terrain and animal life are minimal
  - Human response is primary consideration
- Several practical reduction approaches have been identified
  - Flight below the cutoff Mach number
  - Shaped booms
- Theory, design approaches and benefits have been validated
  - Analysis, ground experiments, simulation, flight tests

Current Research Focus

- Understanding impact of booms heard by people indoors
  - Transmission of the boom sound into a house/building
  - Effects of rattle and startle
- Understanding effect of atmosphere, operations & realistic ground environments
- Full integration of boom reduction into aircraft design
  - Shaping the aft portion of the signature
  - Engine exhaust jet effects
  - Simultaneous design for low boom, high efficiency, light weight, etc
Expanding Design Knowledge

- New target signatures
- More sophisticated analytical and design tools
- Multiple disciplines considered simultaneously
  - Boom, efficiency, takeoff and landing noise, etc.

\[
\text{Shaped Loudness}
\]
\[
\text{Equivalent to:}
\]
\[
0.30 \text{ psf N-wave}
\]
\[
0.23 \text{ psf N-wave}
\]
Future Vision

Efficient, Affordable Supersonic Flight.....

Thank you for your attention!

... with little or no sonic boom noise