Sonic Boom

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Overview

• Part 1: Analysis Tools
  – Witham’s F-function (Analytical)
  – Computational Analysis

• Part 2: Suppression Methodologies
  – Vehicle Shaping
  – Phantom Body Shaping
  – Breakthrough Technologies
Part 1: Analysis Tools

The Sonic Boom, Analysis, and Prediction Tools
The Sonic Boom

• **October 14, 1947**
  – Chuck Yeager breaks the sound barrier
  – Boom prediction/minimization comes to the forefront of research

• **Boom Basics**
  – Multiple shocks form off of many portions of the vehicle
  – Non-linear atmospheric effects tend to coalesce (and attenuate) the waves
  – This non-linear effect produces an ‘N-wave’ signature at the ground level
The Quasi-Linear Analysis

- **Linear Theory**
  - Well known analysis:
    \[
    p = p_0 + \delta p_1 + \delta^2 \rho_2 + \cdots
    \]
    \[
    \tilde{u} = \tilde{u}_0 + \delta \tilde{u}_1 + \delta^2 \tilde{u}_2 + \cdots
    \]
    \[
    \rho = \rho_0 + \delta \rho_1 + \delta^2 \rho_2 + \cdots
    \]
  - Assumes shock disturbances to propagate along parallel characteristic lines
  - Actual flow field has curved parabolic characteristics
    - Thus large errors occur at large distances away from the source (which is a typical flight condition)
The Quasi-Linear Analysis

- **Witham’s Approach**
  - Rather than discard all linearized (simple) relations, Witham & Lighthill used a linearized analysis with some geometric acoustic correctors built in.
  - Restores the $\delta^2$ terms for a higher order of accuracy

- **The Witham F-Function**
  \[
  F(y) = \frac{1}{2\pi} \int_0^y \frac{S''(t)dt}{\sqrt{y-t}}
  \]
  \[
  y = x - \beta r + \left( \frac{(y+1)M^4 F(y) r^{1/2}}{2^{1/2} \beta^{3/2}} \right), \beta = \sqrt{M^2 - 1}
  \]

- **The Pressure Signature (Bernoulli’s Eq)**
  \[
  \frac{p}{p_0} = -\gamma M^2 \left( u + \frac{1}{2} (u^2 + v^2) \right) = \frac{\gamma M^2}{\sqrt{2 \beta}} \frac{F(y)}{r^{1/2}}
  \]

- **Pressure Signature Shape**
  - Resembles the F-function initially
  - As the distance increases characteristics diverge, signature is stretched, and magnitude is attenuated

**Equivalent Area Calculation**
- Each cut is projected onto a plane normal to the flight path
- Area due to volume:
  - Mach plane areas projected onto ‘equivalent axis’
  - Begins and ends at zero area
- Area due to lift:
  \[
  \frac{dA}{dx} = \frac{\beta}{2q} \cdot \sin \theta \cdot \frac{dl}{dx}
  \]
  - Begins at zero, ends at $W\beta/2q$
The Quasi-Linear Analysis

- Modification of the N-wave
  - Maximum overpressure, rise time, and total length of the shock has a major impact on the perceived noise level
  - By modifying the equivalent area (geometry) of the vehicle for given flight conditions, adjustment of these parameters can be accomplished

- Seebass performed an analytical analysis of Witham’s F-function in order to determine what parameters we should adjust
The Quasi-Linear Analysis

• Seebass’ Analysis
  – Three Predominant Conclusions
    • Any improvement in the traditional parameters that govern aircraft efficiency will usually result in a reduction of sonic boom overpressure and impulse
    • The most efficient way to minimize overpressure and impulse is to make the Witham F-function as large as possible as soon as possible (nose blunting)
    • It is always beneficial to increase the aircraft length and stretch out the pressure signal near the vehicle

• Trends
  – Several trends were determined by Seebass’ analysis
  – Depending on the desired minimization (smallest overpressure, largest rise time, etc.) we can find optimal solutions
  – Seebass considered the following signals:

  ![Impulse Minimized](image1)
  ![Overpressure Minimized](image2)
  ![Rise Time Maximized](image3)
The Quasi-Linear Analysis

Fig. 7 Overpressures and impulses as a function of aircraft weight for equal strength front and rear shocks ($H = 25,000$ ft).

Fig. 8 Overpressures and impulses as a function of aircraft length for equal strength front and rear shocks ($H = 25,000$ ft).
Limitations to Witham’s Theory

• Analysis is limited to *slender* bodies of revolution
  – Complex geometries (real geometries) can not be accurately treated

• Near-field limited
  – Analysis is not valid for the near-field
    • This is where typical wind tunnel data would have been taken during the period (or CFD used today)
    • Must be far away enough that the source is considered to be compact and wave propagation to be locally plane
Computational Analysis

• Modern CFD tools can be used for complex geometries
  – CFD allows us to compute the non-axisymmetric pressure signature in the near to mid-field
  – Ideally we would like to compute the pressure field all the way to the far-field (ground-level) but this is computationally intensive.
  – This leads us to the industry standard for computing the far-field pressure signature

• The Thomas method
  – Originally developed for near-to-mid-field wind tunnel test data pressure signatures
  – This method is used today, however, in conjunction with CFD generated pressure signatures
Thomas Method
(Waveform-Parameter Method)

- Use CFD to compute the near-to-mid-field
- Capture a cylinder of pressure
- Use the system of ODE’s below to propagate the pressure signature to the far-field
  - The rates of change of the speed of sound, ambient density, and propagation speed are wrt the ray path

\[
\frac{dm_i}{dt} = C_i m_i^2 + C_2 m_i \\
\frac{d\Delta p_i}{dt} = \frac{1}{2} C_i \Delta p_i (m_i + m_{i-1}) + C_2 \Delta p_i \\
\frac{d\lambda_i}{dt} = -\frac{1}{2} C_i (\Delta p_i + \Delta p_{i+1}) - C_m \lambda_i
\]

\[
C_1 = \frac{\gamma + 1}{2\gamma} \frac{a_0}{p_0 c_n} \\
C_2 = \frac{1}{2} \left( \frac{3}{a_0} \frac{da_0}{dt} + \frac{1}{\rho_0} \frac{d\rho_0}{dt} - 2c_a \frac{dc_a}{dt} - \frac{1}{A} \frac{dA}{dt} \right)
\]

- The Method is Still Limited by the Errors Produced in the Extreme Near-Field
  - 1.5-2.0 body lengths are usually needed to ensure a proper signal
  - However, the method no longer needs to calculate the effective area
Advanced Methods

• Shock Thickness
  – The Thomas method still neglects shock thickness which gives ‘rise’ to the rise time of the overpressure after a shock
  – Lockheed-Martin has developed a ‘Multi-pole’ method in which the Fourier Transform is taken to enforce a rise time

\[ s = 2.5 \Delta x_s \]
Advanced Methods

- Computational cylinder around the vehicle centerline provides interface between near-field CFD solution and far-field flow field.
- Singularities along vehicle axis used to map CFD solution using 11-term Fourier fit (multi-poles).
- Far-field solution calculated from multi-pole strengths.
- Industry-standard Thomas propagation technique used to calculate far-field distribution.

Figure 1 – Multipole Method for Far-Field Correction
Full Potential Method

• High-performance computing
  – Can create a grid to span the entire field to try and use CFD to predict the pressure signature at the ground
  – Very expensive computationally so grid adaptation and shock fitting techniques are employed

• Euler/Potential hybrid solver
  – In the near field an Euler Solver will be employed with a very fine mesh
  – Since the Euler equations do not necessarily satisfy the potential equations a transformation is employed to determine the potential and its derivatives on the interface
  – The potential solver is used to calculate the field signature down to the ground

\[
(\rho \phi_x)_x + (\rho \phi_y)_y + (\rho \phi_z)_z = 0
\]

\[
\rho = \left[1 + \frac{\gamma - 1}{2} M^2 \left(1 - \phi_x^2 - \phi_y^2 - \phi_z^2\right)\right]^{\frac{1}{\gamma - 1}}
\]
Part 2: Suppression Methodologies

Phantom Bodies, Vehicle Shaping, and Breakthrough Technologies
State-of-The-Art Design

• Body Shaping
  – Volume and lift distribution
    • Seebass’ analysis implemented on component design
  – Engine (nacelle) placement
  – Wing reflexing

• Phantom Body
  – Off-body energy addition
  – Force-fields

• Breakthrough Technologies
  – Quiet spike
Vehicle Body Shaping

- Lift-Volume Area Distribution
  - Most effective type of suppression mechanism
    - Distribution tends to be a smooth, long curve with no sharp peaks or kinks
  - Aircraft Weight
    - Smaller aircraft naturally have smaller sonic boom signatures
  - Nose Bluntness
    - Seebass’ Analysis reasons that the F-function should be very large very soon
      - Use large blunt body that maximizes the initial shock strength
      - This causes an increase in drag, which will penalize performance (and boom strength).
      - This method reduces overpressure substantially but results in a ‘plateau’ region of high signature
    - This was successfully used in the SSBD program on a F-5e
Vehicle Body Shaping

Figure 1(b). QSJ Equivalent Area Distribution

Figure 1(c). F-15 Equivalent Area Distribution
Vehicle Body Shaping
Vehicle Body Shaping

- Lift-Volume Area Distribution (Continued)
  - Fuselage Elongation
    - Result consistent with Seebass’ analysis
    - This helps stretch the equivalent area due to volume and thus helps minimize shock strength.
    - If the vehicle is sufficiently long enough a shock can be avoided completely, but this will introduce a large maximum overpressure
  - Wing/Tail Lift Distribution
    - As with volume distribution, lift distribution can help elongate the equivalent area curve as well
      - Long, swept wings are usually preferred in order to maximize the length in which the lifting forces act along the vehicle
      - Tail sections are sometimes chosen to carry 5% or more of the total lift in trimmed flight
        - This helps add lift toward the rear of the vehicle where volume is very small
Vehicle Body Shaping

• Wing Design
  – Maximum Thickness Ratio
    • Shock overpressure decreases as the maximum thickness decreases
      The smaller the thickness ratio, the smaller the shock angle and the weaker the shock
      Consistent with Seebass since smaller thickness ratios lead to favorable lift and drag coefficients
  – Camber Ratio
    • Increasing camber ratio effectively decreases the shock overpressure at the ground level
      Stronger shocks form at the upper surface, weaker shocks form at the lower surface
      Consistent with Seebass since lift and drag coefficients increase with camber ratio (the rate at which they increase is the argument)
  – Nose Angle
    • Attempts to reduce the shock angle that forms off the leading edge
      Seebass: if vehicle efficiency decreases the overpressure will increase (lift and drag are favorable for low nose angles)
    • An optimum exists around 2-3 degrees; Can reduce overpressure by 30% locally

• Combined Design Study
  – Conceptual Design has Seen Benefits as Much as 52% Reduction in Overpressure
Vehicle Body Shaping

- Engine Nacelle Design and Placement
  - External Compression
    - Simple robust design
    - Very significant lip shock
  - Mixed Compression
    - Weaker lip shock
    - Susceptible to inlet unstart
  - Engine Placement
    - Placement on the upper wing provides two-fold benefits
      - Partial shock shielding
      - Weaker (highly swept) shock due to higher local mach numbers
    - Shock mitigation can be accomplished when the engine is placed on the lower wing by wing reflexing
Vehicle Body Shaping

Figure 14 – Under Wing External Compression

Figure 19 – Under Wing Mixed Compression

Figure 15 – Over Wing External Compression

Figure 20 – Over Wing Mixed Compression
Vehicle Body Shaping

Figure 16 – Near Field Pressure Comparison

Figure 17 – External Compression Signatures

Figure 21 – Mixed Compression Ground Signatures
Vehicle Body Shaping

• Wing Reflexing
  – Attempts to cancel out the shock that is formed off of the nacelle by careful design of the wing in that region
  • Only good for design condition if reflexing is fixed
Phantom Body

• The Theory
  – Effectively lengthens the body which elongates the equivalent area distribution

• Force Fields
  – In 1969 Cheng and Goldburg presented a technique using an electrostatic field
    • It ionized oncoming air and gradually turned it to achieve an isentropic compression and (hopefully) avoiding a shock
    • However, they found that these strong interaction forces caused an effective blunt body and detached shock (which aggravated the problem)
  – Their results have been interpreted by many as invalidating any non-mechanical approach
    • However, their results apply only to strong interaction forces
Phantom Body

• Heat Addition
  – A ‘thermal spike’ is created by the projection of heat upstream of the vehicle
    • Replaces the sharp boom by a gradual pressure rise
    • Was first considered in the early 70’s since the necessary length of a vehicle was impractical to build
  – Power requirements are substantial
    • One study determined that a 50-60% power increase is needed for this method
  – On-axis heating is a structural/material concern
    • However, this can be avoided by off-axis heating, but aerodynamics are then of a concern
      – Thermal fins/keels typify this design
  – Studies have shown that heat addition reduces drag substantially
    • Thus only ~30% net power increase is necessary
Phantom Body

Fig. 11 Near-Field Mach Number Color Map for First Heated Design
(M_∞ = 1.4, α = 2.0°, C_L = 0.156, C_D = 0.0119)

Fig. 15 Near-Field Mach Number Color Map for Baseline Unheated Case
(M_∞ = 1.4, α = 2.2°, C_L = 0.156, C_D = 0.0337)
Breakthrough Technologies

• Body Shaping is Limited
  – ‘Conventional’ shaped jets bottom out at around 0.4-0.6 psf overpressure (i.e. no extreme measures such as phantom body)
    • DARPA goal was 0.2-0.3 psf max
• Improving The Signature
  – Make the initial shock weaker
    • This was done with shaping and is ‘maxed out’
    • Also reduces useable fuselage volume
  – Generate additional weaker shocks some distance ahead of the ‘initial’ shock
    • Tailored not allow the shocks to coalesce
• Solution: Quiet Spike
  – A specifically tailored spike that is extendable to design conditions
    • Allows the designer to not sacrifice useable fuselage volume
  – Effectively lengthens body by increasing the slenderness and the equivalent area due to volume in front of the nose
  – Breaks up the shock into a series of weaker shocks allowed to attenuate while not coalescing by specific design
Breakthrough Technologies

**Figure 5(a)** Two Stage Quiet Spike Geometry

**Figure 5(b)** Two Stage Quiet Spike Ground Signature
Breakthrough Technologies

United States Patent
Henne et al.

Gulfstream QSJ with Quiet Spike™

Computational Fluid Analysis
Breakthrough Technologies

- Ground Signature Pay-off
  - Increases rise time to over 40 ms
  - Maximum overpressure due to any shock is less than 0.15 psf, well within the DARPA goal

- How Loud is the Signature?
  - The signature was propagated using Thomas so no shock thickness is included. If we use the estimation of a hyperbolic tangent rise time we get the superimposed ‘smoothed’ signal
  - If the signature is approximated as a sine curve a frequency of 5 hz would be inaudible.
  - Predicted SPL is 55 dB(A) or 10,000 times < than Concord
  - The signature will be audible even if the general shape is near that of a sine wave since higher frequency ‘wiggles’ are present
Breakthrough Technologies

Progress in Sonic Boom Suppression

QSJ Advanced+ A-Weighted Sound Energy Quieter Than Concorde By A Factor of 10,000

>35dB Reduction

Sonic Boom
Configuration
Gulfstream Whisper

dB

City Traffic
Talking

dB(A)
References