Conceptual Design of Low-Boom Aircraft with Flight Trim Requirement

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Outline

• Introduction and motivation
• Formulation of trim-feasible low-boom targets
• Verification of center of pressure sensitivity
• Application to design of a low-boom demonstrator
• Summary
Introduction and Motivation

Low-boom aircraft design

• Exploration of a complex design space with contradicting environmental and performance objectives

• Inverse design approach leverages the natural decoupling in the sonic boom analysis requirements

• Lift tailoring can lead to configurations incapable of trim through traditional fuel management techniques

• Achieving trim after configuration is shaped for low-boom can result in a compromised design

Source: Mathias Wintzer, AMA
Introduction and Motivation

Exploration of trim requirement

- Several lifting devices explored to help redistribute lift of low-boom configuration with minimal success
  - Canard and strake
  - Attempt to trade volume for lift fore of CG
  - Can work for some configurations but not an overarching solution
  - Can lead to structurally unacceptable configurations due to the volume trade necessary to maintain low-boom

- Approach needed to account for trim requirement early in design process
  - Leverage sonic boom analysis decoupling and inverse design
  - Introduce trim objective into the low-boom target generation process
  - Drive the design concurrently to a trimmed and low-boom state
Description of Sonic Boom Analysis

• CFD analysis with Cart3D\textsuperscript{1}
  – Inviscid CFD analysis package geared toward conceptual and preliminary aerodynamic design
  – Cartesian volume mesh rotated by Mach angle to align the shocks with the computational grid and decrease numerical dissipation

• Atmospheric Propagation with sBOOM\textsuperscript{2}
  – Solve the augmented Burgers equation
  – Account for atmospheric losses due to nonlinearity, molecular relaxation, and thermo-viscous absorption
  – Propagate pressure distribution backward in time to calculate an equivalent area (Ae) in the neighborhood of the configuration

\textsuperscript{1}Aftosmis, Berger, and Adomavicius, AIAA-2000-0808., \textsuperscript{2}Rallabhandi, AIAA-2011-1278.
Formulation of Trim-Feasible Low-Boom Target

Calculation of a surrogate axial lift distribution

- Reversed $\Delta e$ is calculated by propagating a pressure distribution backward in time to a region near the configuration
- $\Delta e$ is the error in classical $e$ which fails to capture the three-dimensional flow effects associated with a real configuration
- Mixed-fidelity$^4$ $e$ design approach
  - Change in $\Delta e$ due to minor shape deformation is relatively small
  - Change in reversed $e$ can be approximated by the change in classical $e$

Formulation of Trim-Feasible Low-Boom Target

Calculation of a surrogate axial lift distribution

- Change in volume $A_e$ between design iterations assumed to be small
Formulation of Trim-Feasible Low-Boom Target

Calculation of a surrogate axial lift distribution

- Change in volume $A_e$ between design iterations assumed to be small
- Change in classical $A_e$ is a result of a change in the lift component of classical $A_e$
- Change in reversed $A_e$ is a result of a change in the lift distribution

![Diagram showing classical and reversed lift distributions with annotations for change due to lift.](image-url)
Formulation of Trim-Feasible Low-Boom Target

Calculation of a surrogate axial lift distribution

- Change in volume $Ae$ between design iterations assumed to be small
- Change in classical $Ae$ is a result of a change in the lift component of classical $Ae$
- Change in reversed $Ae$ is a result of a change in the lift distribution
- Leverage sonic boom analysis decoupling by optimizing a target $Ae$ for low-boom
Formulation of Trim-Feasible Low-Boom Target

Calculation of a surrogate axial lift distribution

- Change in volume $\Delta e$ between design iterations assumed to be small
- Change in classical $\Delta e$ is a result of a change in the lift component of classical $\Delta e$
- Change in reversed $\Delta e$ is a result of a change in the lift distribution
- Leverage sonic boom analysis decoupling by optimizing a target $\Delta e$ for low-boom
- Surrogate lift $\Delta e$ is calculated by correcting the lift $\Delta e$ of the baseline with predicted change in lift $\Delta e$
- Predicted change in lift distribution is used as an optimization objective for trim
Formulation of Trim-Feasible Low-Boom Target

**Calculation of surrogate center of pressure**

- Assume an aircraft of high fineness ratio (i.e. pitching moment due to drag is small)
- Axial lift distribution calculated from surrogate lift $A_e$
- Surrogate lift $A_e$ distribution is mapped onto the baseline configuration
- Longitudinal location of section centroids calculated at each equivalent distance and used as the moment arm to calculate CP

![Diagram of aircraft with labels for center of gravity (CG), center of pressure (CP), section centroids, and lift distribution.]
Formulation of Trim-Feasible Low-Boom Target

Target optimization process

Inputs:
- Baseline reversed Ae
- Baseline lift component of classical Ae

Linked Parameters:
- \( L_1 \): Spline control points for target Ae
- \( L_2 \): Target Ae
- \( L_3 \): Propagation altitude based on end value of surrogate Ae due to lift
- \( L_4 \): Target Ae
- \( L_5 \): Change in surrogate CP
- \( L_6 \): Perceived loudness
Verification of Center of Pressure Sensitivity

- **Case I.** Sensitivity based on shaping of a wing-body-tail configuration
  - Verify that approximated CP based only on lift closely matches CP based on pressure distribution

- **Case II.** Sensitivity based on shaping of a demonstrator concept
  - Verify sensitivity of surrogate CP on realistic low-boom concept
  - Verify that shaping of the configuration to match a low-boom target also produces the desired shift in CP

- **Case III.** Practical design of a demonstrator concept
  - Verify that a non-trimmed but low-boom feasible concept can be redesigned using a trim-feasible low-boom target
Verification of Center of Pressure Sensitivity

Case I: Sensitivity based on shaping of a wing-body-tail configuration

- Deformation consists of linear wing tip twist of -1 deg and +1 deg
- Observed good agreement between CP calculated from CFD surface pressure distribution, lift Ae, and surrogate lift Ae
- Maximum difference between the CP based on lift Ae and actual CP is 0.87 percent
- **Confirms that if contribution of drag to pitching moment is small then lift Ae is sufficiently accurate to predict CP**
Verification of Center of Pressure Sensitivity

Case II: Sensitivity based on shaping of a demonstrator concept

- Wing camber at the root midchord is varied incrementally by 0.5 ft from -1 ft to +1 ft
- Horizontal tail tip twist is varied incrementally by 0.5 deg from -1 deg to +1 deg with a fixed incidence angle
- Sensitivity of CP calculated with the surrogate lift Ae shows good agreement with sensitivity of CP calculated using CFD-based surface pressure distribution
Verification of Center of Pressure Sensitivity

Case III: Practical design of a demonstrator concept

- Initially shaped to match a low-boom target $A_e$ in the absence of trim constraint
- Untrimmed CG is 7.6 ft fore of CP
- Unable to trim by fuel management or without major layout rearrangement
- **Wing redesign to match new target shifts the CP within 0.3 ft of CG**

![Graph showing the verification of Center of Pressure Sensitivity]
Baseline configuration

- Length: 108 ft
- Height: 30 ft
- Width: 23 ft
- Angle: 13 deg
Mass properties, propulsion system, and trim analysis

- Conceptual design methods\(^5\) used to calculate mass properties, CG, and mission performance
- Propulsion system is a semi-embedded F404-402
- Engine performance calculated with NPSS\(^6\) using publicly available data
- Cruise design point
  - Mach 1.6, altitude of 50,000 ft, and weight of 21,000 lb
  - Most aft CG located at 84.5 ft
  - Required forward shift in CP for trim is 1.6 ft
Application to Design of a Low-Boom Demonstrator

Generation of trim-feasible low-boom target

- Pareto frontier generated for PLdB and change surrogate CP using NSGA-II\textsuperscript{7} optimizer in ModelCenter\textsuperscript{8}
- Altitude is allowed to vary to expand the design space
- A CP margin is used to account for uncertainty in weight calculation
- Selected trim-feasible target
  - Produces a 65.9 PLdB ground signature with a predicted forward shift in CP of 4.2 ft
  - Requires a cruise altitude of 51,700 ft

\textsuperscript{7}Srinivas and Deb, 1995., \textsuperscript{8}Phoenix Integration.
Lift tailoring used to match new trim-feasible target

- Adjusted angle of attack of baseline configuration to meet CL at new cruise altitude
- Implemented wing camber parameterization scheme with 15 design variables (5 span and 3 chord locations)
- Used H-tail incidence angle to control aft lift
- Performed interactive design using mixed-fidelity approach to match the target $A_e$
- Used inboard wing sections to control the required lift increase fore of the CG
- Used outboard wing sections to correct aft $A_e$ deviation

Baseline

Design
Application to Design of a Low-Boom Demonstrator

Comparison of surface pressure distribution

Baseline – Upper Surface

Design (Shaped Baseline) – Upper Surface

Baseline – Lower Surface

Design (Shaped Baseline) – Lower Surface
Summary

• Demonstrated a low-boom target generation approach that accounts for trim requirement
  – Based on mixed-fidelity design approach
  – CP calculated from an approximate axial lift distribution
  – Assume an aircraft with high fineness ratio and relatively small pitching moment contribution from drag force
• Provided three numerical cases that verify the accuracy of the sensitivity for the approximated CP
• Demonstrated the trim-feasible target generation approach for the early conceptual design of a low-boom demonstrator concept

Significance

• Provide new understanding of the design space, design feasibility, and flight conditions (i.e. altitude) required to achieve a trimmed low-boom aircraft
• Avoid costly design compromises needed to achieve trim of an aircraft initially designed strictly for low-boom
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Questions?
References


Backup Slides
Design Evolution

**T-tail, S-duct F404, and 125 ft**
- Redesign of 140 ft configuration to reduce size
- Replaced F100 engine in 140 ft concept with F404
- Inlet shortened to reduce complexity and efficiency losses
- Successfully trimmed and shaped this configuration close to a low-boom target

**T-tail, S-duct F404, and 108 ft**
- Redesign of 125 ft configuration to further reduce size
- Successfully trimmed and shaped this configuration close to a low-boom target with 65.9 PLdB
Generation of Trim-Feasible Low-Boom Target

Incorporate trim requirement into the low-boom target generation process

• Based on mixed-fidelity* Ae design approach.
• Provide an approximation of CP for an aircraft configuration with a reversed Ae matching a low-boom Ae target.
• Provide new understanding of the design space, design feasibility, and cruise flight conditions (i.e., altitude) to achieve a trimmed low-boom aircraft.
• Avoid costly design compromises needed to achieve trim of an aircraft initially designed strictly for low-boom.

Target optimization process

Linked Parameters:
L₁ : Spline control points for target Ae
L₂ : Target Ae
L₃ : Propagation altitude based on end value of surrogate Ae due to lift
L₄ : Target Ae
L₅ : Change in surrogate CP
L₆ : Perceived loudness
Generation of Trim-Feasible Low-Boom Target

Application of trim-feasible target generation to T-tail, S-duct F404, 110 ft concept

- Initial aerodynamic and boom analysis of baseline conducted at 50,000 ft
- CP calculated with Cart3D to be X=86.1 ft
- Low-fidelity aft most CG (X=84.5 ft) calculated to determine required shift in CP for trim
- Pareto frontier generated for PLdB and surrogate CP using NSGA-II optimizer in ModelCenter
- Selected low-boom target produces a 65.9 PLdB signature with a 4.2 ft forward shift in CP
- A CP margin is used to account for uncertainty in weight calculation
- Trim-feasible target requires cruise altitude of 51,700 ft

Figure shows lift redistribution requirement
Outline

• Introduction and motivation
  – Trim Problem in Low-Boom Design
• Approach, significance, and numerical results
• Formulation of trim-feasible low-boom targets
  – Calculation of surrogate axial lift distribution
  – Calculation of surrogate center of pressure
  – Optimization process
• Verification of center of pressure sensitivity
  – Sensitivity based on shaping of a wing-body-tail configuration
  – Sensitivity based on shaping of a demonstrator concept
  – Practical design of a demonstrator concept
• Conceptual design of a low-boom demonstrator
  – Description of sonic boom analysis
  – Description of baseline configuration
  – Mass properties, propulsion system, and trim analysis
  – Generation of trim-feasible target
  – Description of low-boom design and trim process
• Summary
Introduction to Trim Problem in Low-Boom Design

- Classical equivalent area distribution
Approach

• Introduce a trim objective into the low-boom target generation process by using a CP based on an approximation of Ae due to lift for a presumed design

Significance

• Provide new understanding of the design space, design feasibility, and cruise flight conditions (i.e., altitude) required to achieve a trimmed low-boom aircraft
• Avoid costly design compromises needed to achieve trim of an aircraft initially designed strictly for low-boom

Numerical Results

• Verification of proposed approach conducted through numerical experiments
• Application to early conceptual design of low-boom demonstrator
• Engine installation introduces volume requirement that results in an Ae distribution “bump” that is difficult to overcome for low-boom
• Embedded engine installation alleviates problem at the cost of integration complexity
Introduction and Motivation

- Engine installation introduces volume requirement that results in an $A_e$ distribution “bump” that is difficult to overcome for low-boom
- Embedded engine installation alleviates problem at the cost of integration complexity
Introduction and Motivation

- Engine installation introduces volume requirement that results in an Ae distribution “bump” that is difficult to overcome for low-boom.
- Embedded engine installation alleviates problem at the cost of integration complexity.
- Deficit in Ae aft of engine is corrected through addition of volume or lift.
- Redistribution of lift aft of CG is unfavorable for trim but necessary for low-boom design.
Formulation of Trim-Feasible Low-Boom Target

Calculation of a surrogate axial lift distribution

- Mixed-fidelity\(^2\) Ae design approach
  
  \[ A_{e,\text{mixed}} = A_{e,\text{rev, baseline}} - A_{e,\text{Mach, baseline}} + A_{e,\text{Mach, design}} \]

- Change in volume Ae between design iterations is assumed to be small and reversed Ae of design is set equal to target Ae

- Surrogate lift Ae for the design is scaled based on \(\Delta A_e\) of baseline configuration

\[ A_{e,\text{design, lift}} = A_{e,\text{target}} - A_{e,\text{rev, baseline}} + A_{e,\text{baseline, lift}} \]

\(^1\text{Li and Rallabhandi, 2014.} \quad ^2\text{Ordaz and Li, AIAA-2013-2660.}\]
Conceptual Design of a Low-Boom Demonstrator

Description of baseline configuration
• Single semi-embedded engine
• T-tail empennage
• T-38 cockpit