Shock Wave Reduction via Wing-Strut Geometry Design

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SHORT VERSION
Shock Wave Reduction via Wing-Strut Geometry Design

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- Designing Approach
  Fixed LE&TE, larger LE radius, fixed max thickness  For Wing & Strut
  Step 1: 2D optimization (not technically accurate but illuminating)
  Step 2: 3D manually design

- Pressure Distribution Oriented Multi-Objective Optimization Design
  - CFD Solver: NSAWET
  - Opt Algorithm: NSGAII / DE ( & Continuous Adjoint Method based on NSAWET)
  - Modeling/ Deformation: CST (14 design var. for an airfoil), etc.
  - Surrogate-Assisted Opt: Kriging / RBF

- Pressure Distribution Oriented:
  - As objectives: accelerate performance opt / manipulate flow structure
  - As constraints: robustness consideration, etc.

- Application in Industry (COMAC C919, etc.)
  - Man-in-Loop: Introducing engineer’s experience, supervision and manipulation
  - Low Accuracy for Turn-around Time: 2.75D (2D) design, coarse grid

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Shock Wave Reduction via Wing-Strut Geometry Design

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- Designing Approach
  - Step 1: 2D optimization (GA Algorithm)
    - 20 cores 2 hour (population size 32, 12 generations) to gain good enough results
  - Step 2: 3D manually design (6 airfoils)
    - Final design has a total 9.8 count drag reduction (10mil cells)
    - The span load is basically kept the same

<table>
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Cruise Point Results (Ma=0.72 AoA=1deg)
Most wave within the modification region (Y=15~17) can be reduced
Separation can be significantly reduced once the shock wave disappears
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FULL VERSION
Shock Wave Reduction via Wing-Strut Geometry Design

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Outline

- Background
- Original Configuration
- Design Approach
- Design Result
- Conclusion

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Background

Objectives:
Minimize shock wave and interference drag in the strut-wing junction region in cruise condition

Using flow control technologies or optimization strategies

The challenge:
Flow control applied to reduce interference and wave drag in cruise condition.

Iso-surface Definition:
\[ shock\_wave\_flag = \vec{M} \cdot \frac{\nabla p}{|\nabla p|} = 1.1 \]
Cruise Condition

- Flight Coefficients
  \- \( Ma = 0.72 \)
  \- \( \text{AoA} = 1 \text{ deg} \)
  \- \( Re = 7.1E6/m \)
  \- \( \text{Altitude} = 30000\text{ft} \)
  \- \( \text{Pressure} = 30089.59\text{Pa} \)
  \- \( \text{Tempera} = 228.71\text{K} \)
  \- \( \text{Cp}^* (M=1) = -0.88 \)
Original Configuration

- Foils of Wing/Strut in different sections are the same
  - Aspect Ratio = 24.3 (wing) / 38.4 (strut)
  - Root/Tip Ratio = 3.3 (wing) / 0.0 (strut)
  - Sweep Angle (0.5chord) = 13.3 deg

- Cruise condition
  - CL = 0.203  Cd=0.01135  Cm=0.757

Iso-surface Definition:

\[ \text{shock\_wave\_flag} = \vec{M} \cdot \frac{\nabla p}{|\nabla p|} = 1.1 \]

Span load: Blue Line is the Elliptical distribution
Original Configuration

- **Mach Contour**
  - Strut has influence on the wing lower surface even when the distance is relatively long. (Y=7)
  - When the wing and strut are near, they form a “nozzle”, causing a strong shock wave. (Y=16)
Original Configuration

- **Mach Contour**
  - `shock_wave_flag = 1.1` roughly means `Ma` in front of wave = 1.2
  - Strong shock wave exists beyond modification region (`Y<14.5`)
  - Joint region has significant separation (`Y=16.5`)
Ma=0.72 AoA=1.0deg
Off-Design Cp of the Original Config

- Ma=0.72 AoA=1.0deg (Cruise Point)
- Ma=0.72 AoA=3.0deg
- Ma=0.72 AoA=5.0deg
- Ma=0.68 AoA=1.0deg
- Ma=0.68 AoA=3.0deg
- Ma=0.68 AoA=5.0deg
Ma=0.72 AoA=1.0deg

Junction Region
Ma=0.72 AoA=3.0deg

Junction Region
Ma=0.72 AoA=5.0deg

Junction Region

![Graphs showing pressure distribution across different sections (Y=13, Y=15, Y=16, Z=1.00, Z=0.85).]
Ma=0.68 AoA=1.0deg

Junction Region
Ma=0.68 AoA=3.0deg

Junction Region

Tsinghua University
Ma=0.68 AoA=5.0deg

Junction Region
Off-Design Cp of the Original Config

- For different AoA (CL), shock wave between wing lower surface and strut upper surface are basically unchanged => Strong Wave

Ma=0.72 AoA=1.0deg

Ma=0.72 AoA=3.0deg

Ma=0.72 AoA=5.0deg
Off-Design Cp of the Original Config

- For lower Mach, strong wave between wing & strut still exists

Ma=0.72 AoA=1.0deg

Ma=0.68 AoA=1.0deg
Summary

- Strong wave exists in design and off design conditions
- Flow between wing lower surface & strut upper surface seems insensitive to the flight condition, and it looks like the flow phenomenon of a nozzle
- Due to the small sweep angle, 3D effect caused by cross flow should not be strong

Therefore,

- A geometry modification to the stream-wise area distribution to avoid a “nozzle” is the first idea
- 2D simulation may not be accurate, but may be illuminating
Design approach
Constraints

- angle of attack of the airplane can be modified, so that the final solution matches the lift of the initial reference configuration
- strut attachment location cannot be modified (both chord and spanwise attachment location)
- strut thickness can not be reduced
- the length of the vertical portion of the strut which is attached to the wing cannot be extended, but its shape (tow angle, airfoil profile, etc) are free
Constraints

- upper wing surface cannot be modified
- wing twist angle cannot be modified (fixed leading edge and trailing edge)
- lower surface of the wing can be modified only between the planes
- $y = 14.5$ m
- $y = 17.5$ m
- wing thickness cannot be reduced from the reference geometry. Reference lower wing surface cannot be penetrated by the final geometry
Constraints

- ALLOWED GEOMETRY MODIFICATION
  - any region of the strut and lower wing surface that have not been constrained in the previous two sections and between the following two planes
    - \( y = 14.5 \text{ m} \)
    - \( y = 17.5 \text{ m} \)

- ALLOWED REGIONS FOR FLOW CONTROL INSTALLATIONS
  - anywhere between the following two planes
    - \( y = 14.5 \text{ m} \)
    - \( y = 17.5 \text{ m} \)
Case Definition

- **Allowed Region (Y=14.5m~17.5m)**
  
  For smoothness consideration, actual geometry modification is limited within **Y=15m~17m**

- **Constraints**
  
  Basically being limited to airfoil design with thickness constraint
  
  Wing upper surface can not be modified

- **Flight Condition**
  
  Fixed lift design
  
  Ma = 0.72
  
  Re = 7.1E6/m
  
  CL = 0.203
Optimization Design

- 2D trial optimization
- Section Y=15 (Slice from 3D result)

Original 3D
Ma=0.72 AoA=1.0 Re=7.1mil
Section CL=0.42

Original foil in 2D Calculation
Ma=0.7 AoA=1.03 Re=7.1mil
CL=0.532 Cd=0.02920
Optimization Design

- 2D trial optimization
- Section Y=15 (Slice from 3D result)

- 2D calculation can give some idea of the “nozzle” phenomenon: the “nozzles” are similar between 3D and 2D, and the Cp of wing upper surface & strut lower surface differ
- We focus on the “nozzle”,
- get a 2D optimized foil design (fixed AoA)
2D trial optimization => Install to 3D configuration
Section Y=15 (Slice from 3D result)

Ma=0.7 AoA=1.03 Re=7.1mil
CL=0.3709 Cd=0.01438
Optimization Design

- 2D optimized foil in 3D
- Section Y=15 (Slice from 3D result)
- Wave still exists, i.e. 2D ≠ 3D in the junction region
- However, when far away from the junction, 2D ~ 3D (Y=11)
Optimization Design

- After the 2D trail optimization giving us some idea how to reduce shock wave, a series of manually designing progresses are engaged.
- The key is to avoid stream-wise convergent-divergent flow (flow acceleration), however the modification is limited due to the unchanged wing upper surface and thickness constraint.
- Some additional constraints are also applied for robustness consideration, like minimum leading edge radius, etc.
RESULT
Design V.S. Original
Design Result

- Final design has a total 5 count drag reduction

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- The span load is basically kept the same
Separation Bubble

- junction region has separation
- The final design has remaining wave in the joint region, along with the wall interference, causes the separation not significantly reduced
- Iso-surface (gray) is defined by $Ma=0.2$
Foil Unchanged

Wing

Strut
Wing

Strut

Y=15.5
Off-Design Performance

- Design at $Ma=0.68$ can eliminate all strong wave (original still has)
- Separation can be significantly reduced

$Ma=0.68$ $AoA=1.0\text{deg}$
Cruise Point

Ma=0.72
AoA=1deg

Slice Contour: Mach
Surface Contour: Cp
Iso-surface: wave_flag=1.1
Low Mach

Ma=0.68
AoA=1deg

Slice Contour: Mach
Surface Contour: Cp
Iso-surface: wave_flag=1.1
Further Modification

- Expand the modification region to $Y=11$ to $17$
- The remaining wave and separation can be further reduced
- (Previously $Y=15$ to $17$)

Figure 4 Shock Wave of a Further Design (Design Region: $Y=11$ to $Y=17$)
Conclusion

- The interference between wing and strut
  Not negligible even when they are relatively far away (Y=4)
  Junction region acting like a nozzle, causes strong wave
  Separation exists

- Geometry modification
  Basic idea is modifying the “nozzle” streamwise area distribution
  Avoid flow acceleration between wing lower surface and strut upper surface
Conclusion

- Geometry modification can reduce wave
  
  Most wave within the modification region ($Y=15\sim17$) can be reduced
  
  A total 5 count drag reduction is achieved
  
  Expand the region, remaining wave can be further reduced
  
  And the separation can be also reduced
Thank You

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