Shock Wave Reduction via Wing-Strut Geometry Design

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PADRI, Barcelona (Spain) 2017.11.29

SHORT VERSION

Shock Wave Reduction via Wing-Strut Geometry Design

Runze LI, Wei NIU, Haixin CHEN* Tsinghua University, Beijing, China

- 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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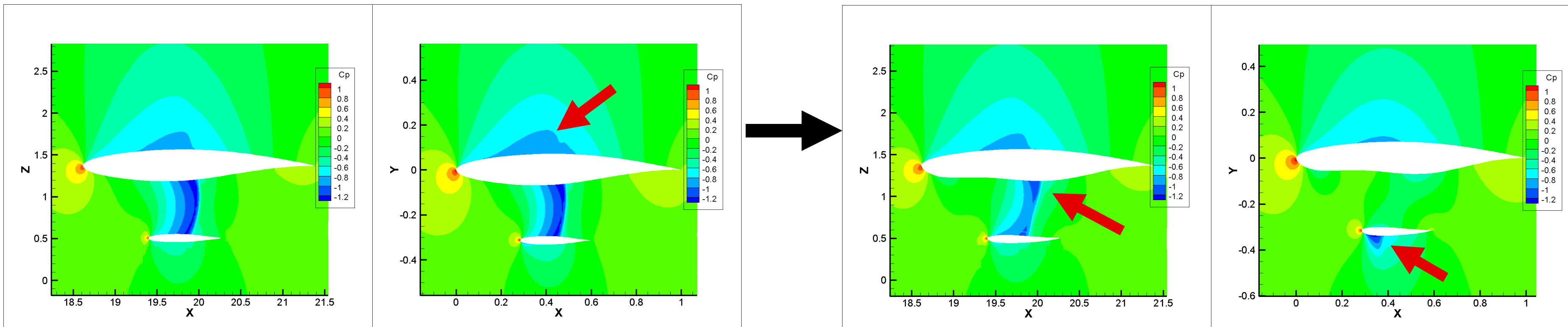
- Designing Approach

  Step 1: 2D optimization (GA Algorithm)

  20 cores 2 hour (population size 32, 12 generations) to gain good enough results

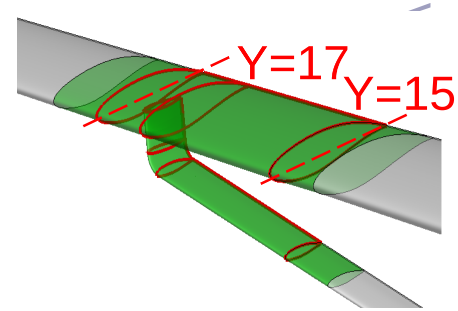


Original 3D Slice | Original foil in 2D Calculation | 2D Optimized foil in 3D | 2D Optimized foil

  Step 2: 3D manually design (6 airfoils)

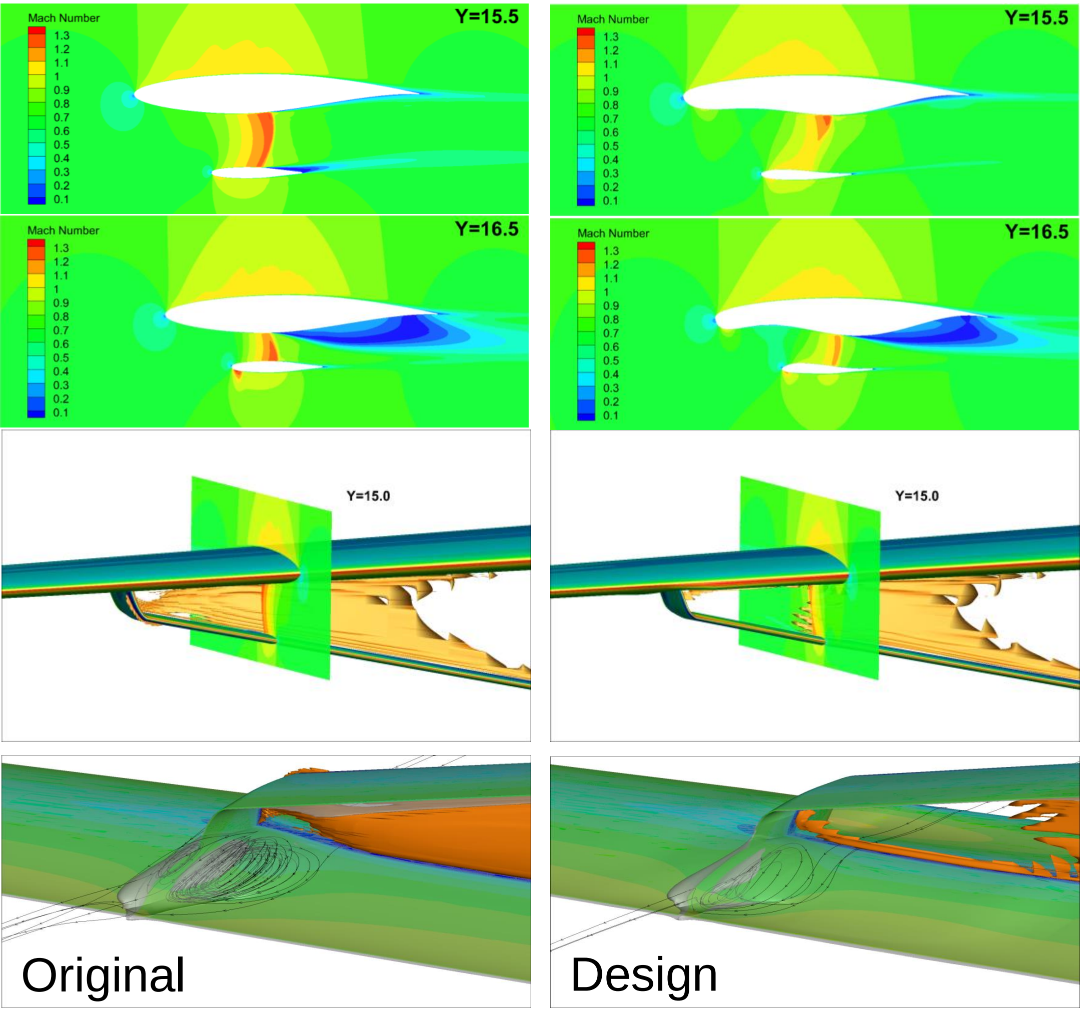
- Final design has a total 9.8 count drag reduction (10mil cells)
- The span load is basically kept the same

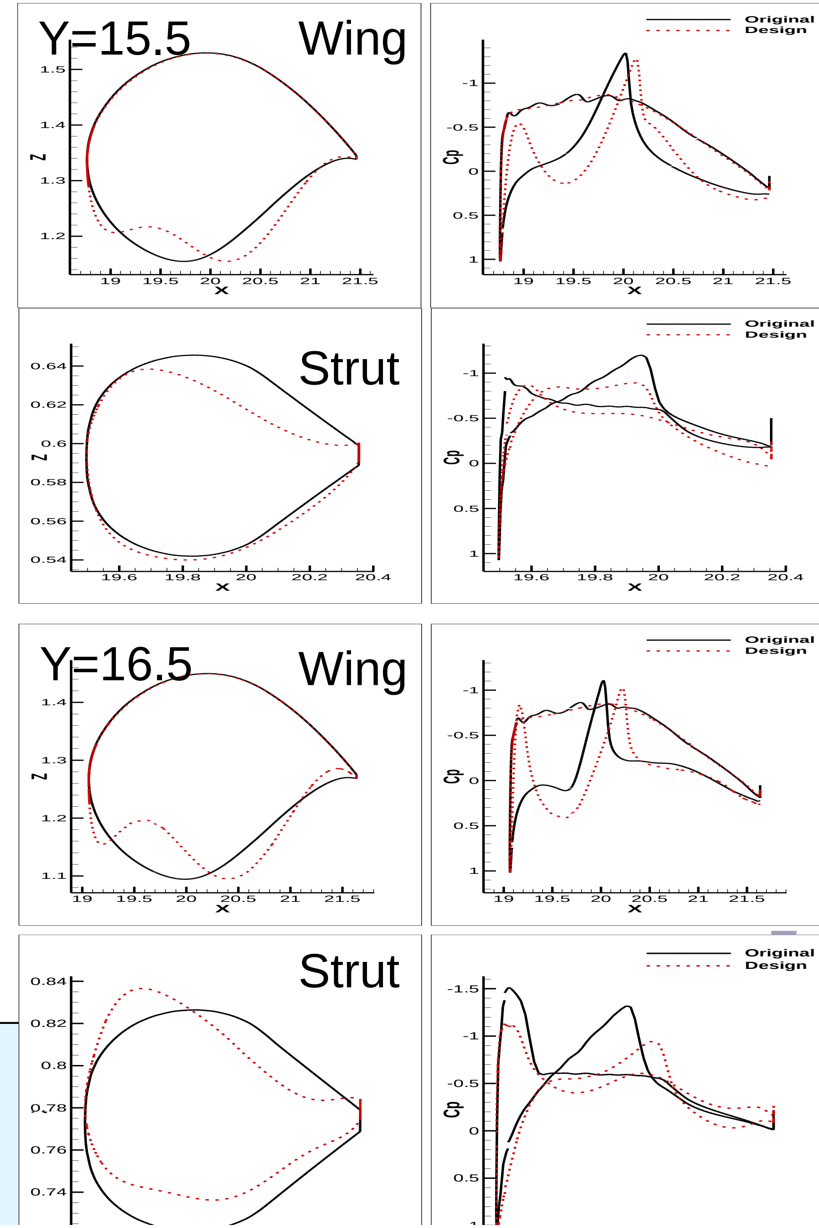
	Lift Coefficient	Total Drag Coefficient
Original	0.406	0.02270
Design	0.406	0.02162

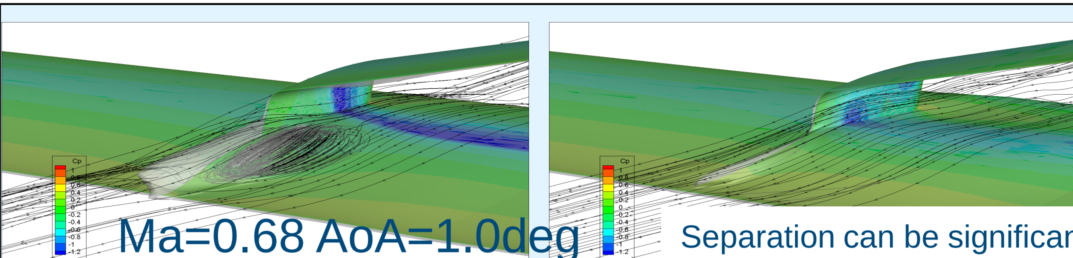


Cruise Point Results (Ma=0.72 AoA=1deg)

Most wave within the modification region (Y=15~17) can be reduced







Separation can be significantly reduced once the shock wave disappears

FULL VERSION

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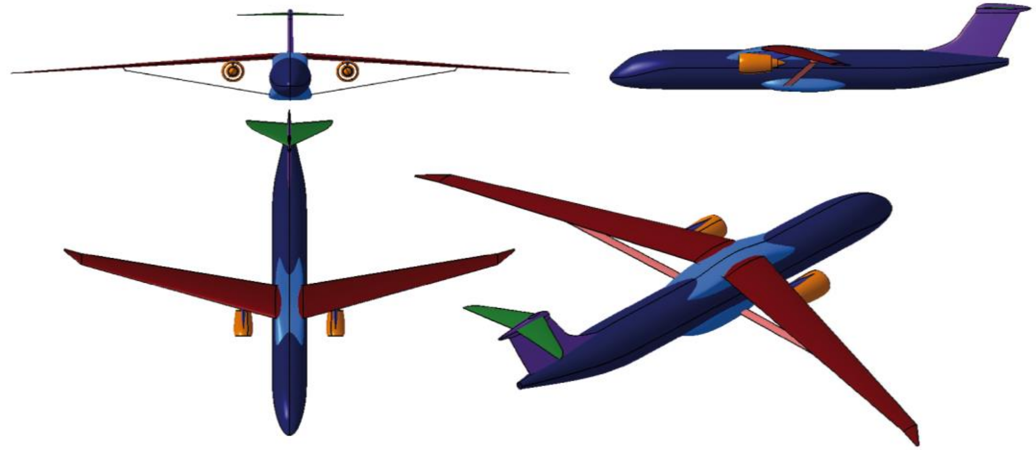
Outline

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

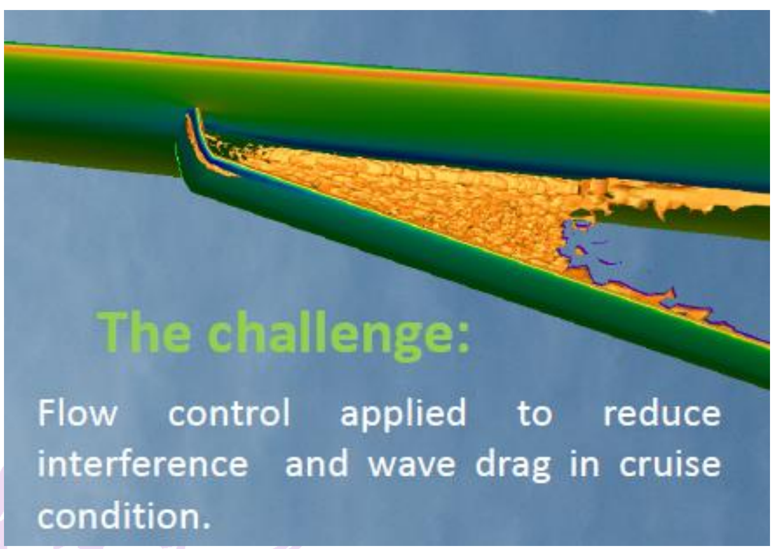
Background



- Objectives:

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

  Using flow control technologies or optimization strategies



Iso-surface Definition:

$$shock\_wave\_flag = \vec{M} \cdot \frac{\nabla p}{|\nabla p|} = 1.1$$

Cruise Condition

- Flight Coefficients

Ma	= 0.72
AoA	= 1 deg
Re	= 7.1E6/m
Altitude	= 30000ft
Pressure	= 30089.59Pa
Tempera	= 228.71K
Cp* (M=1)	= -0.88

Original Configuration

- Foils of Wing/Strut in different sections are the same

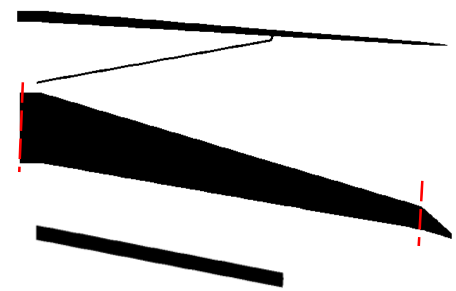
  Aspect Ratio = 24.3 (wing) / 38.4 (strut)

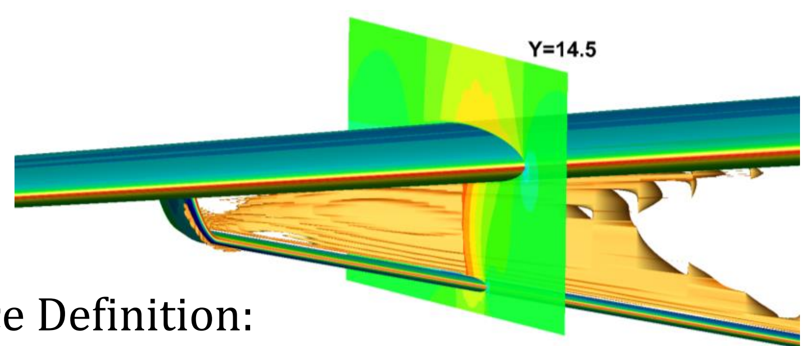
  Root/Tip Ratio = 3.3 (wing) / 0.0 (strut)

  Sweep Angle (0.5chord) = 13.3 deg

- Cruise condition

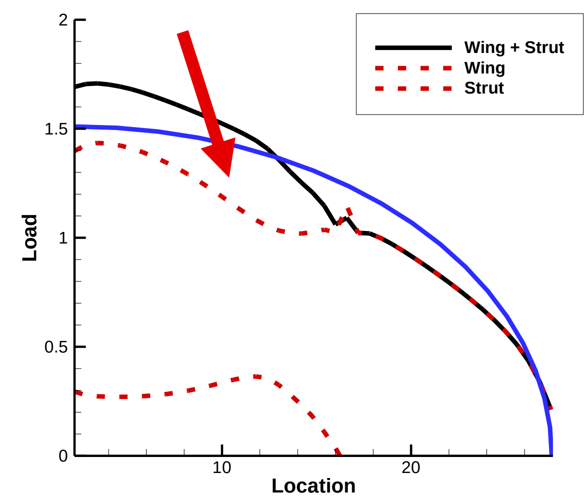
  CL = 0.203 Cd=0.01135 Cm=0.757





Iso-surface Definition:

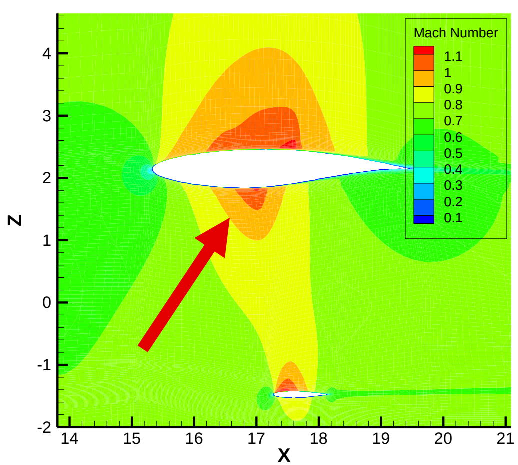
$$shock\_wave\_flag = \vec{M} \cdot \frac{\nabla p}{|\nabla p|} = 1.1$$



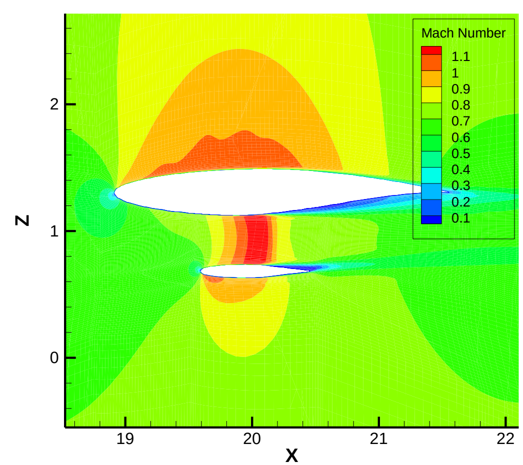
Span load: Blue Line is the Elliptical distribution

Original Configuration

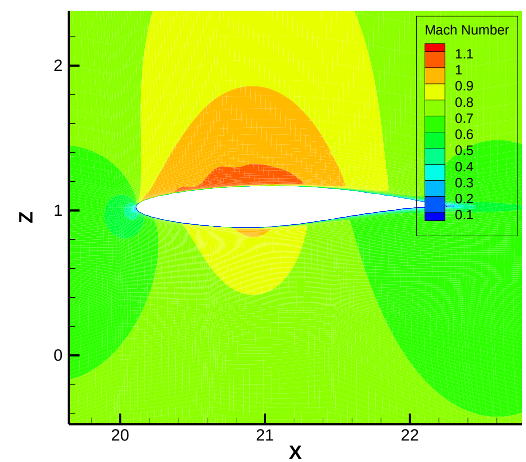
- Mach Contour
  - Strut has influence on the wing lower surface even when the distance is relatively long. (Y=7)
  - When the wing and strut are near, they form a “nozzle”, causing a strong shock wave. (Y=16)



Y=4



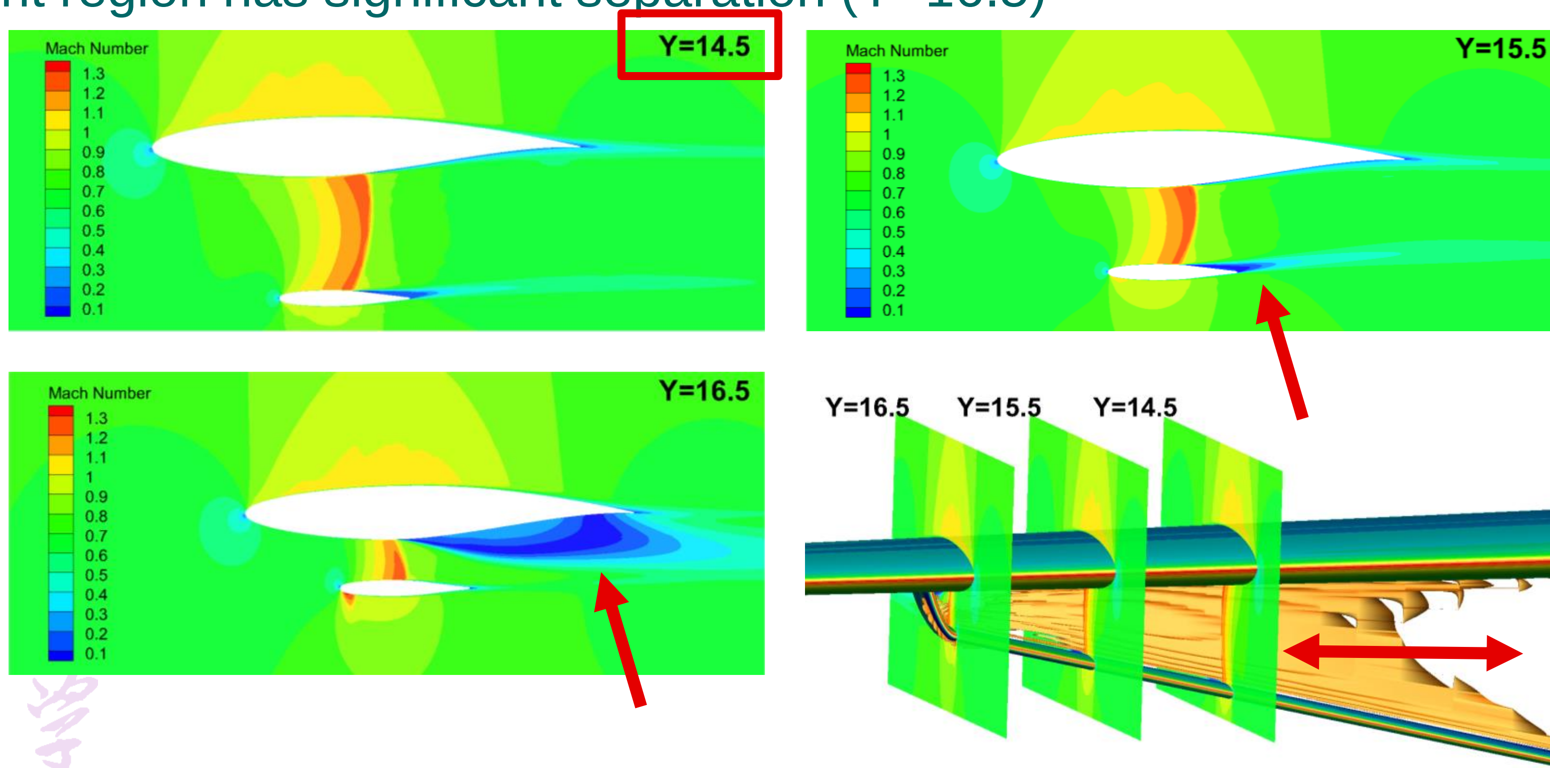
Y=16



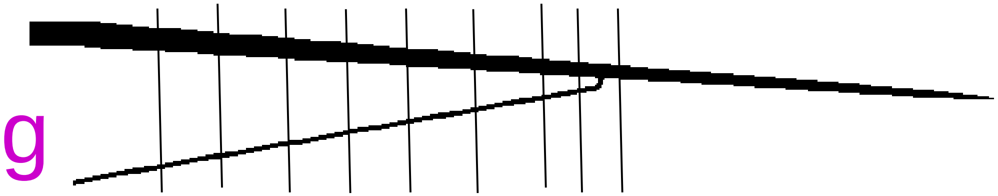
Y=20

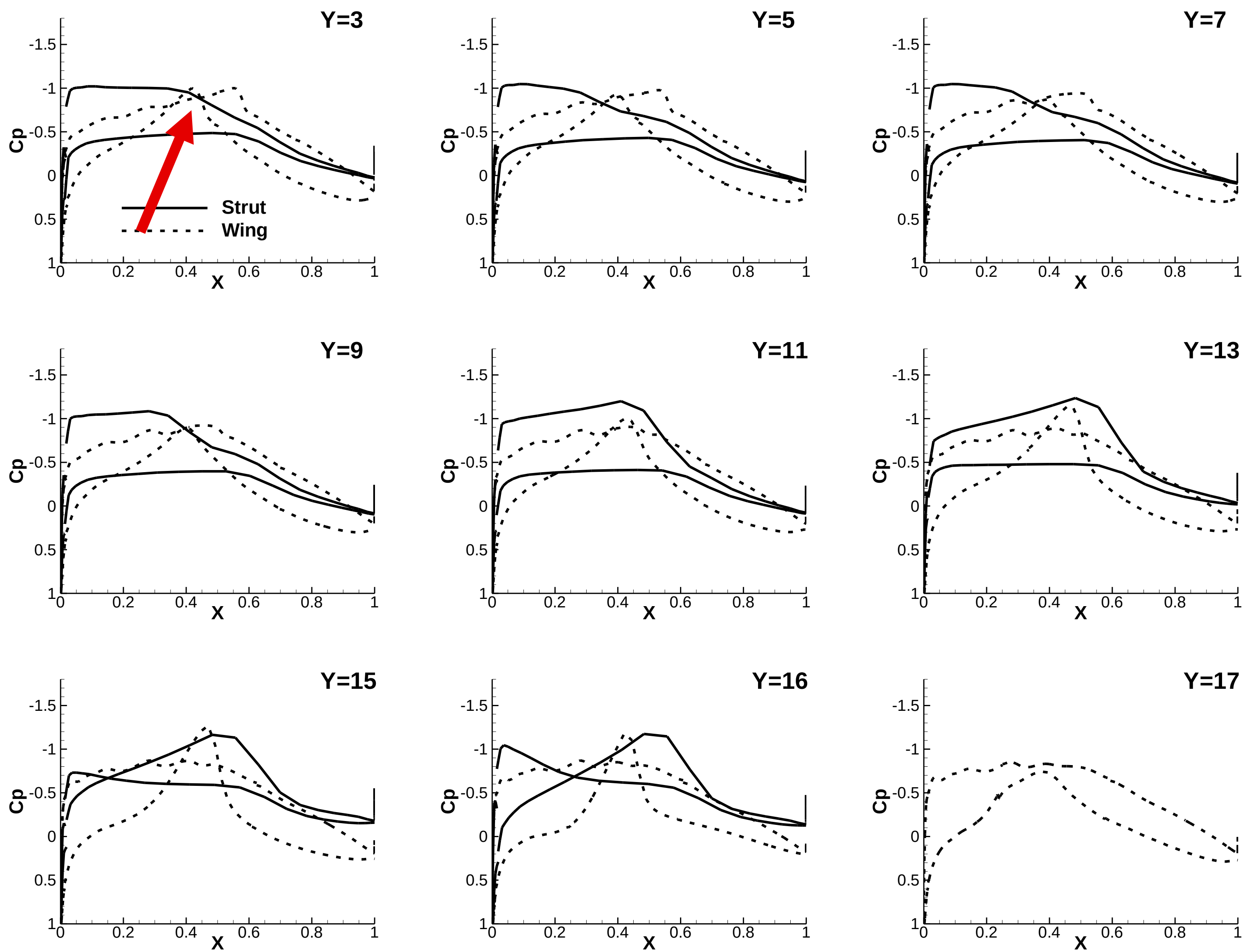
Original Configuration

- 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



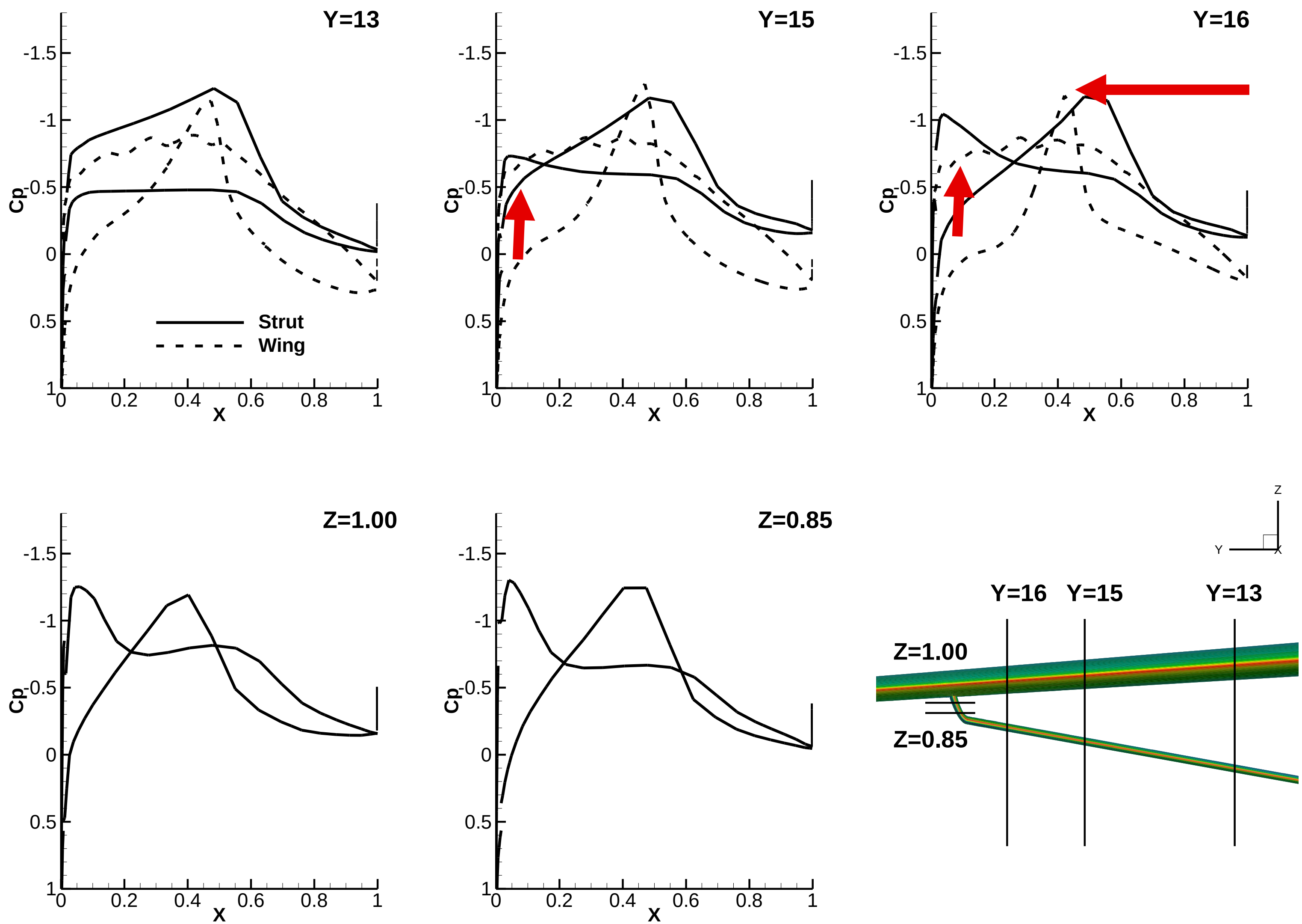


Off-Design Cp of the Original Config

- 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

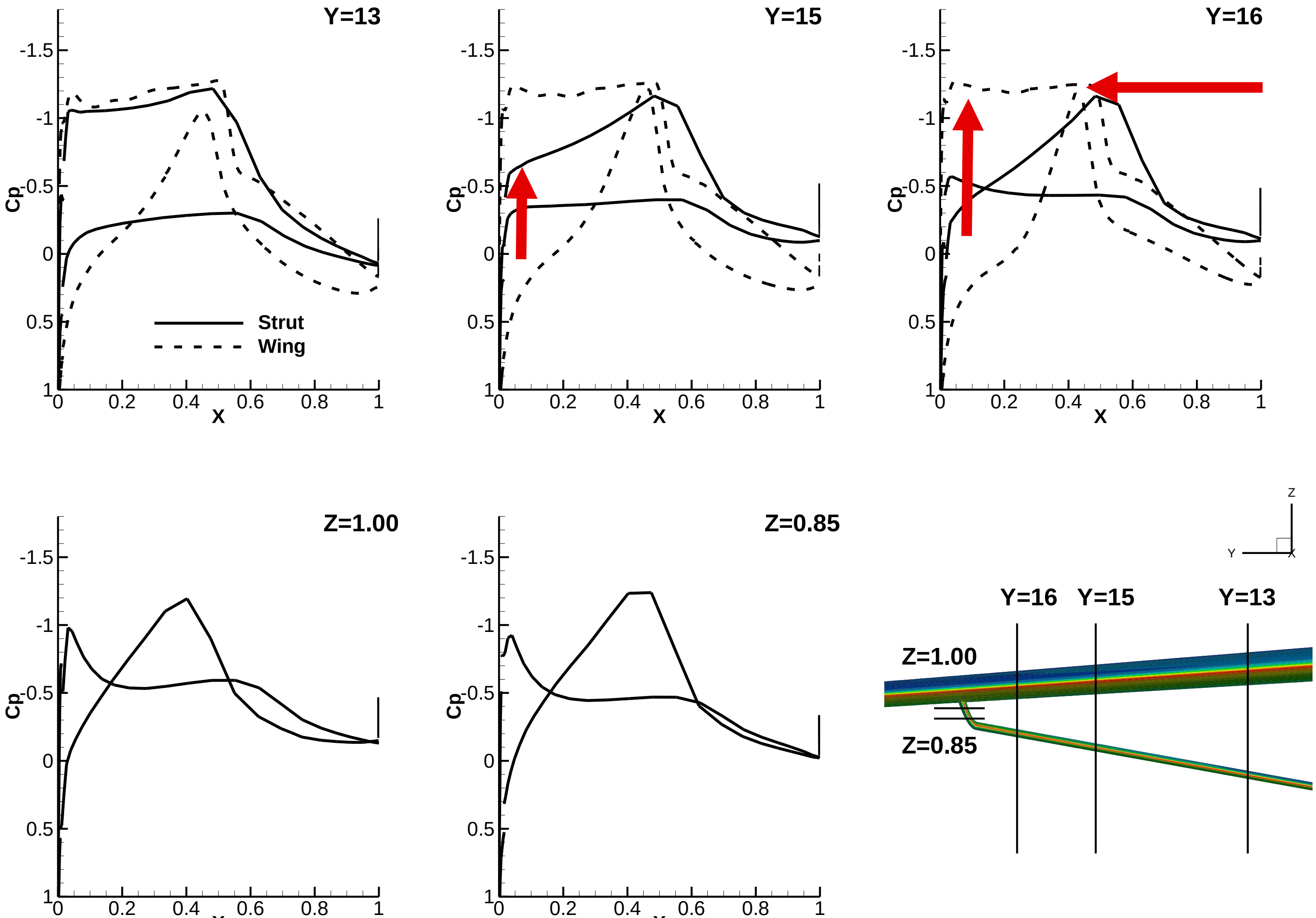
Ma=0.72 AoA=1.0deg

Junction Region



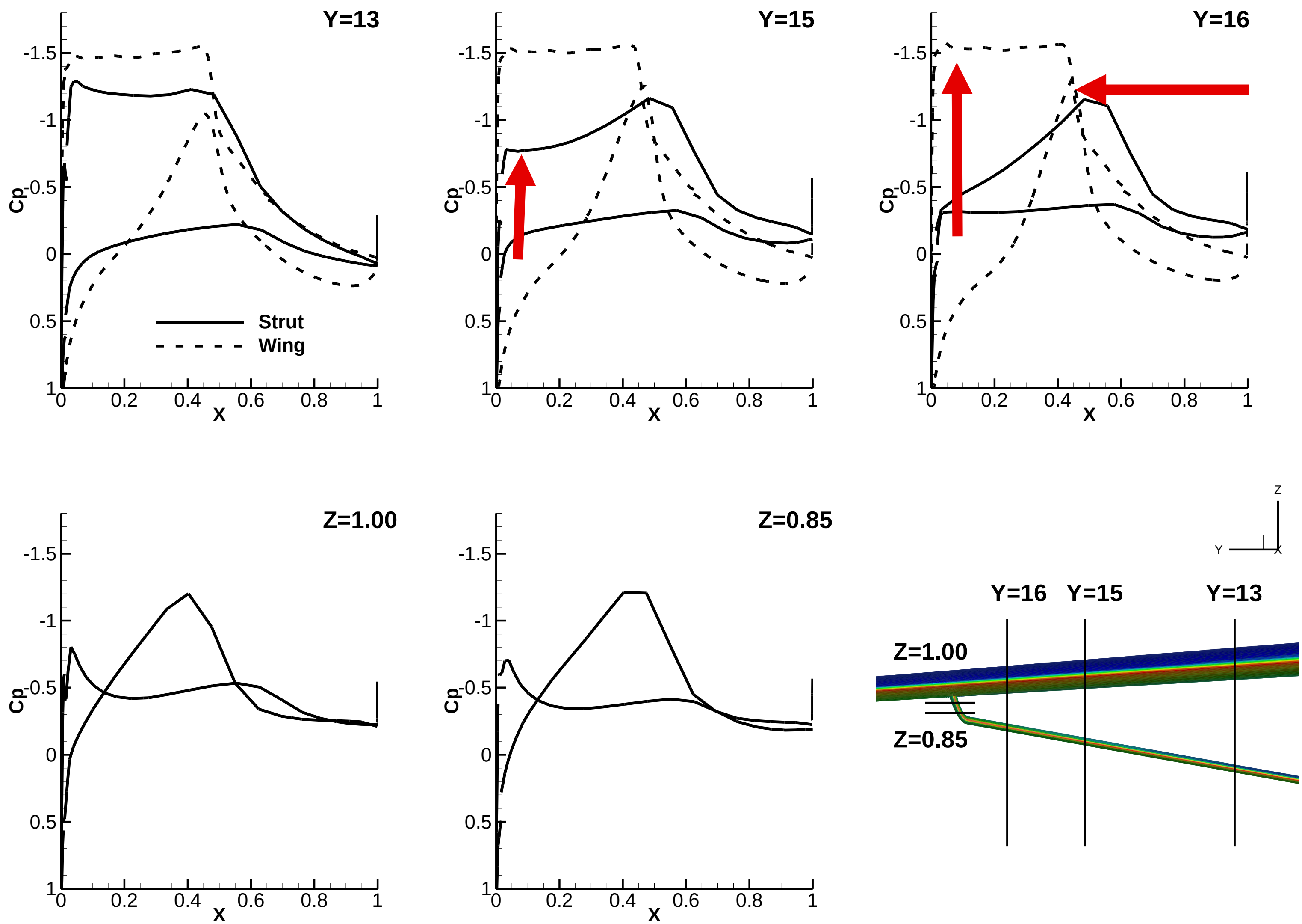
Ma=0.72 AoA=3.0deg

Junction Region



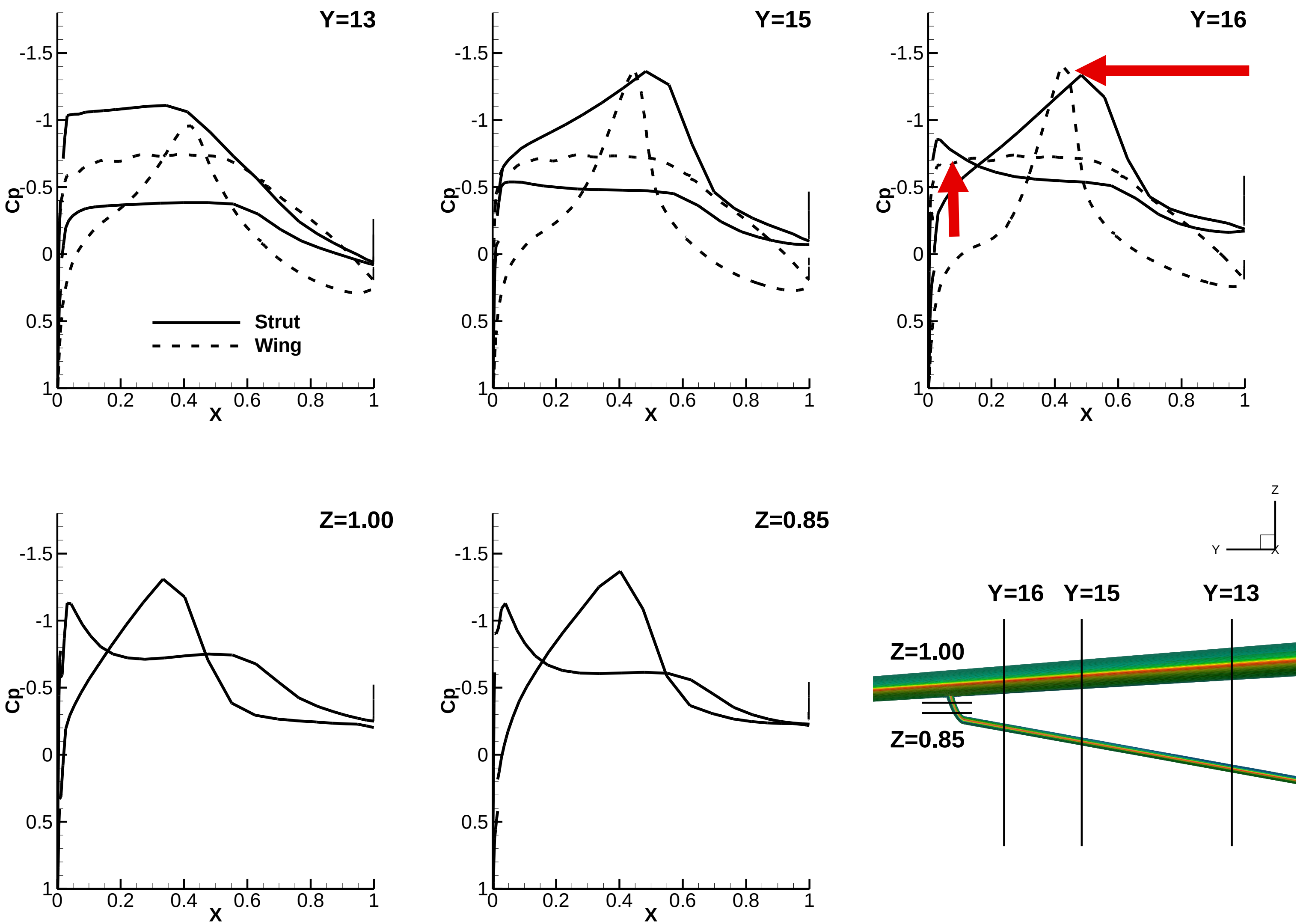
Ma=0.72 AoA=5.0deg

Junction Region



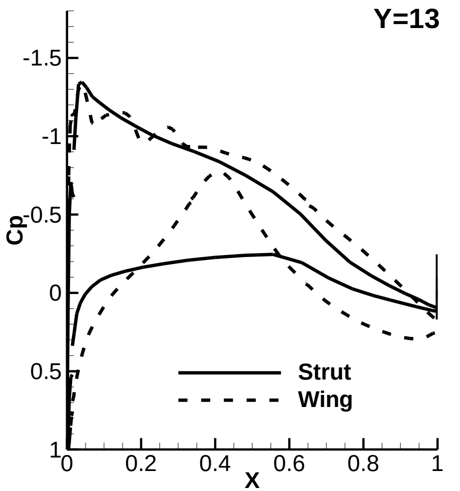
Ma=0.68 AoA=1.0deg

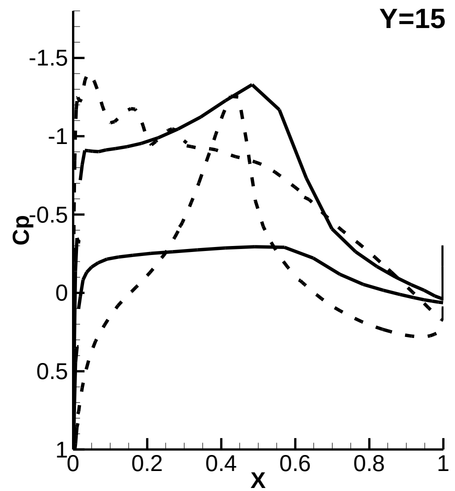
Junction Region

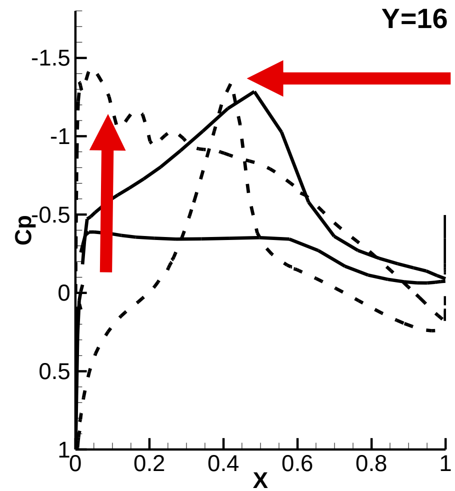


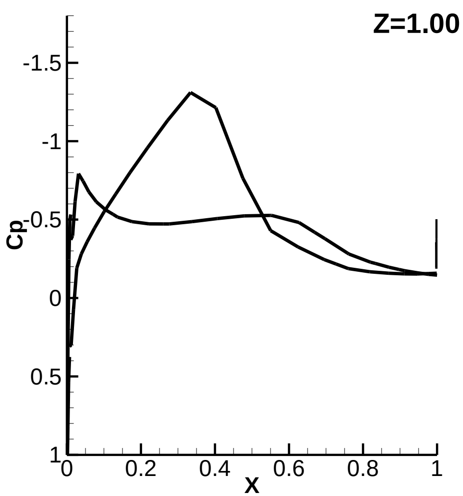
Ma=0.68 AoA=3.0deg

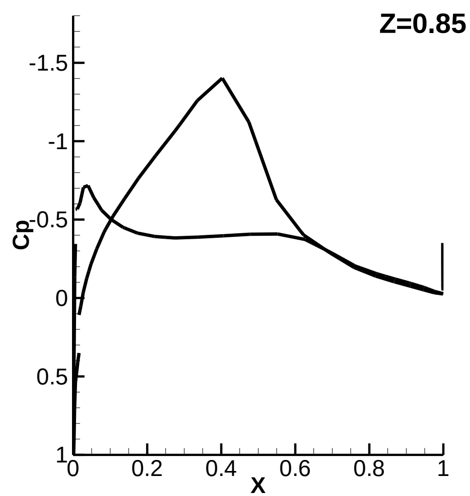
Junction Region

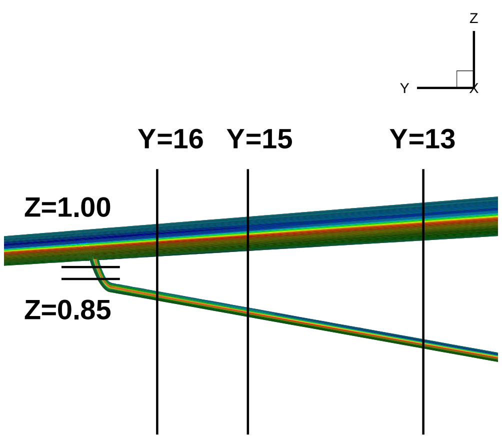






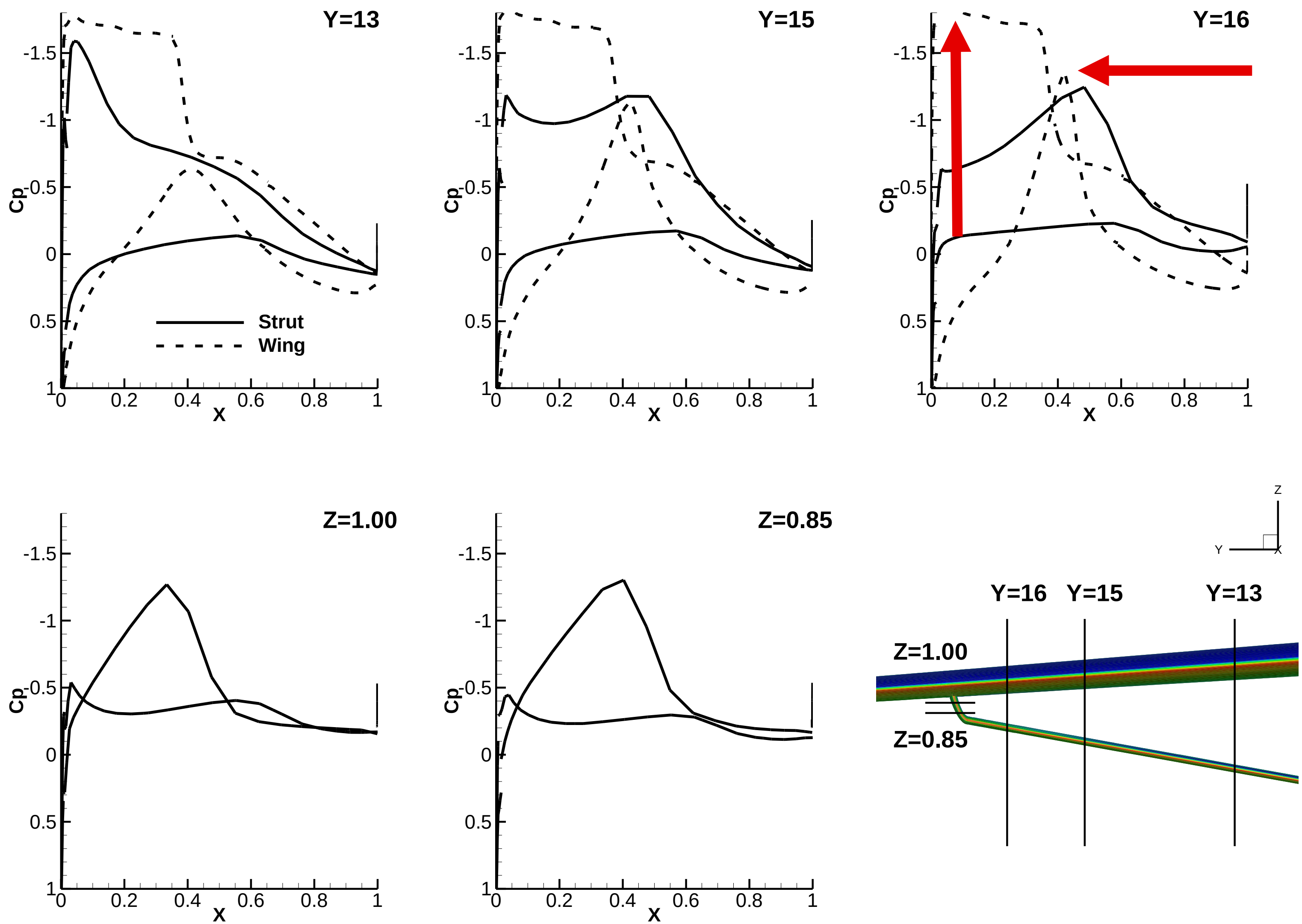






Ma=0.68 AoA=5.0deg

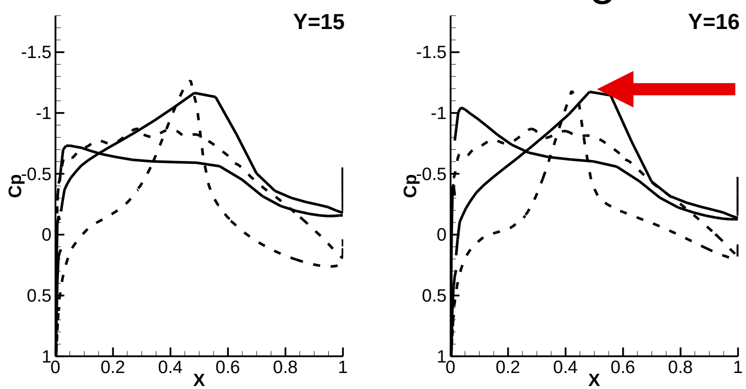
Junction Region



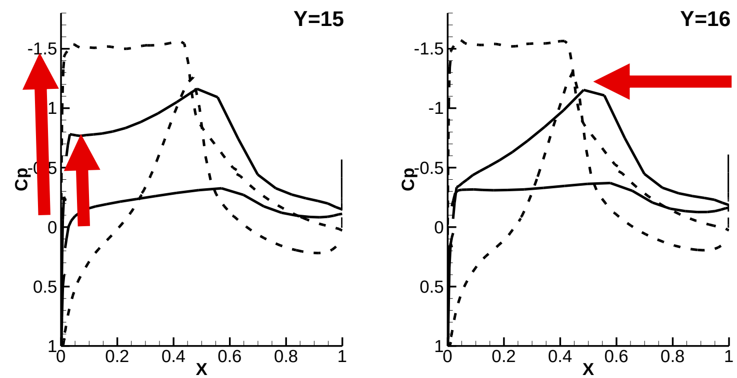
Off-Design Cp of the Original Config

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

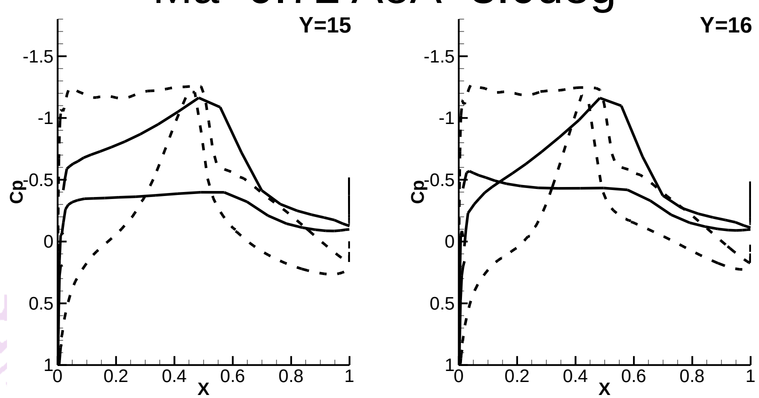
Ma=0.72 AoA=1.0deg

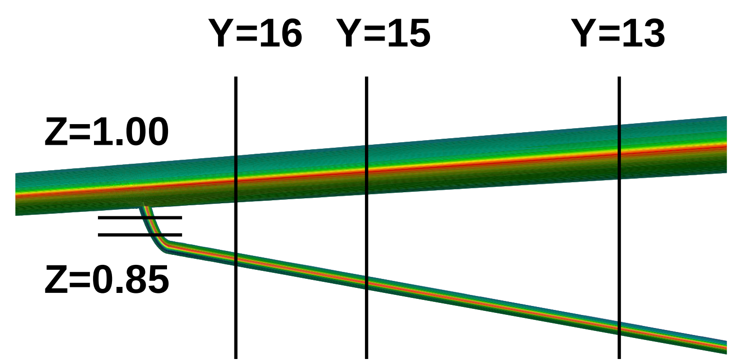


Ma=0.72 AoA=5.0deg



Ma=0.72 AoA=3.0deg

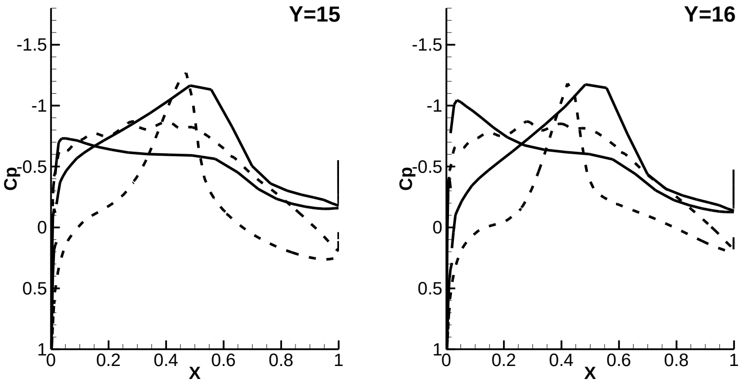




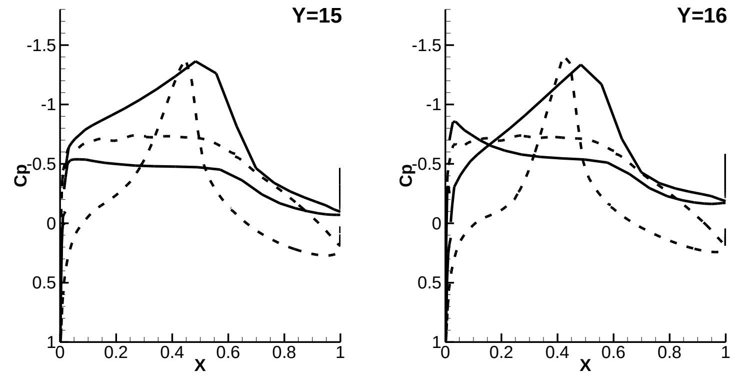
Off-Design Cp of the Original Config

- 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

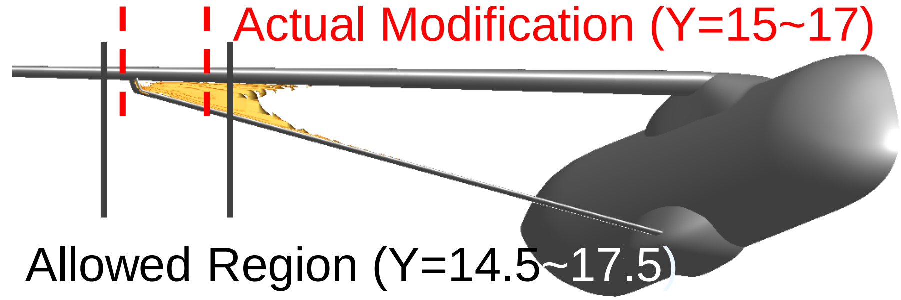
Constraints

- 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 m
- y = 17.5 m
- ALLOWED REGIONS FOR FLOW CONTROL INSTALLATIONS
- anywhere between the following two planes
- y= 14.5 m
- y = 17.5 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

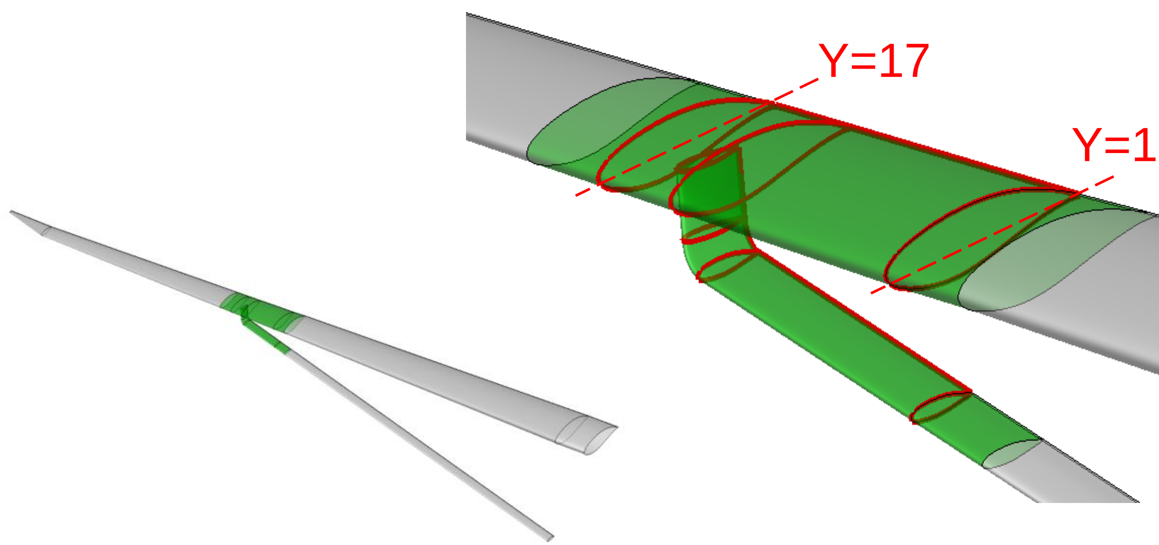
- Flight Condition

  Fixed lift design

  Ma = 0.72

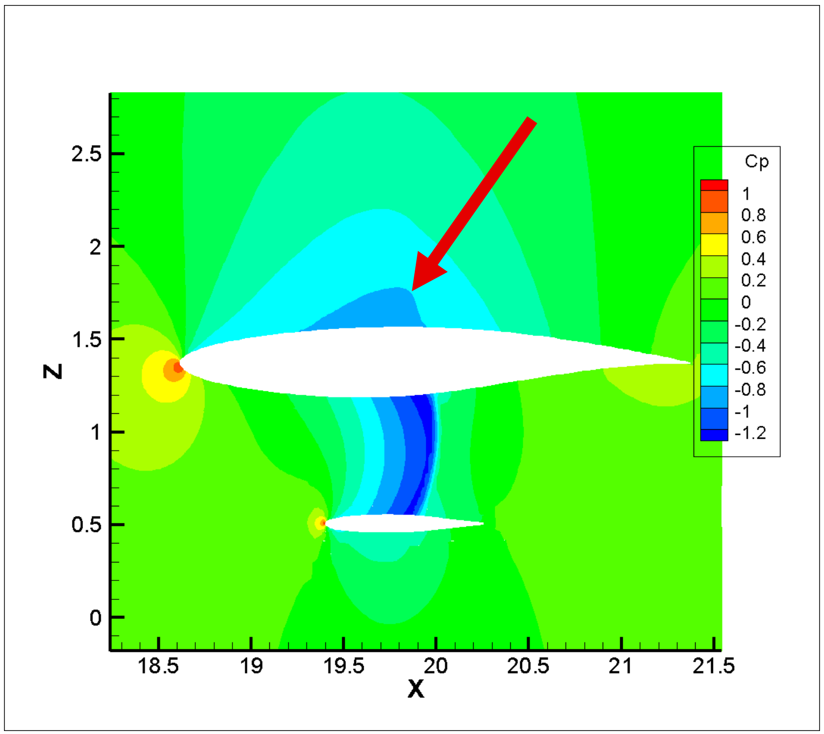
  Re = 7.1E6/m

  CL = 0.203

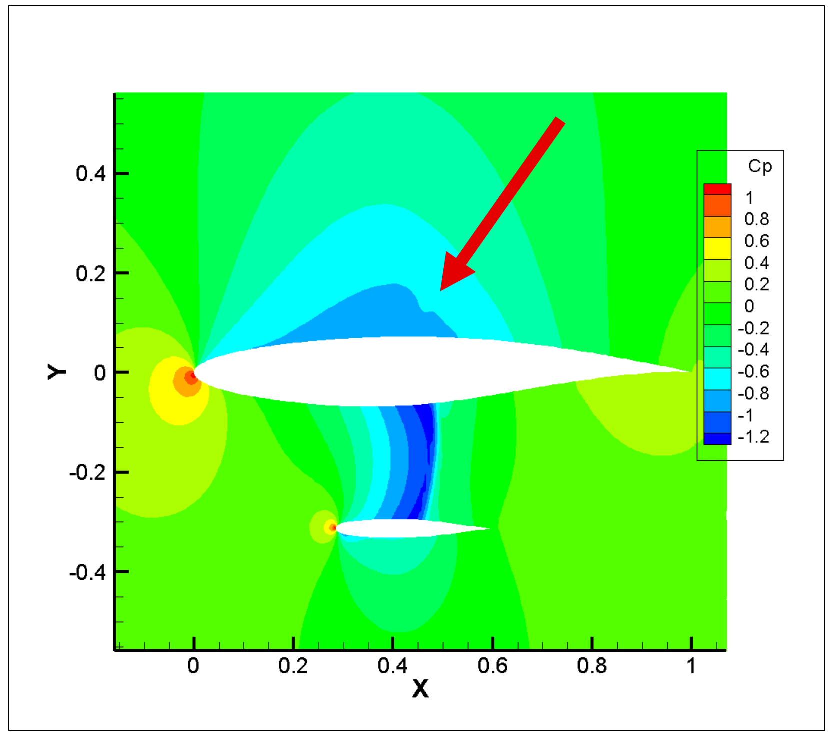


Optimization Design

- 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

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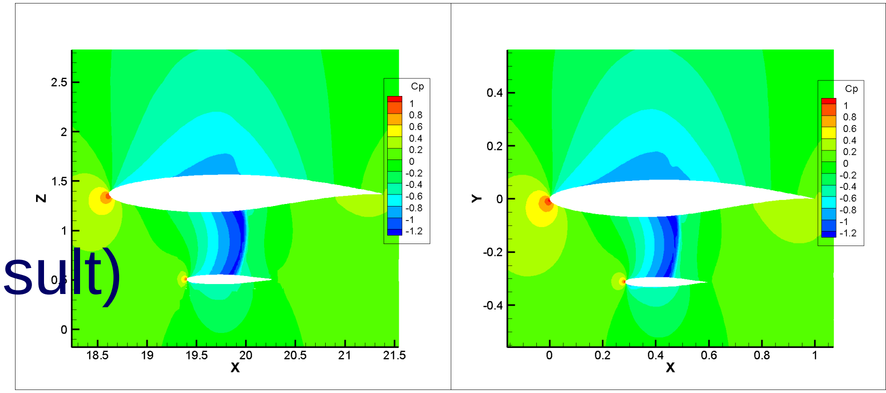
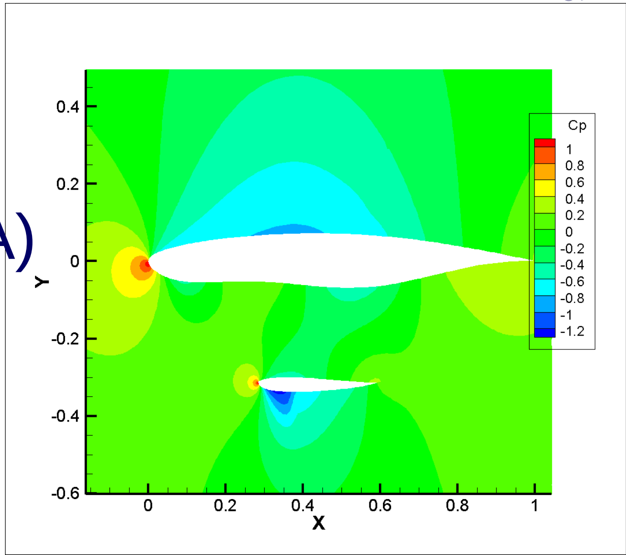
Optimization Design



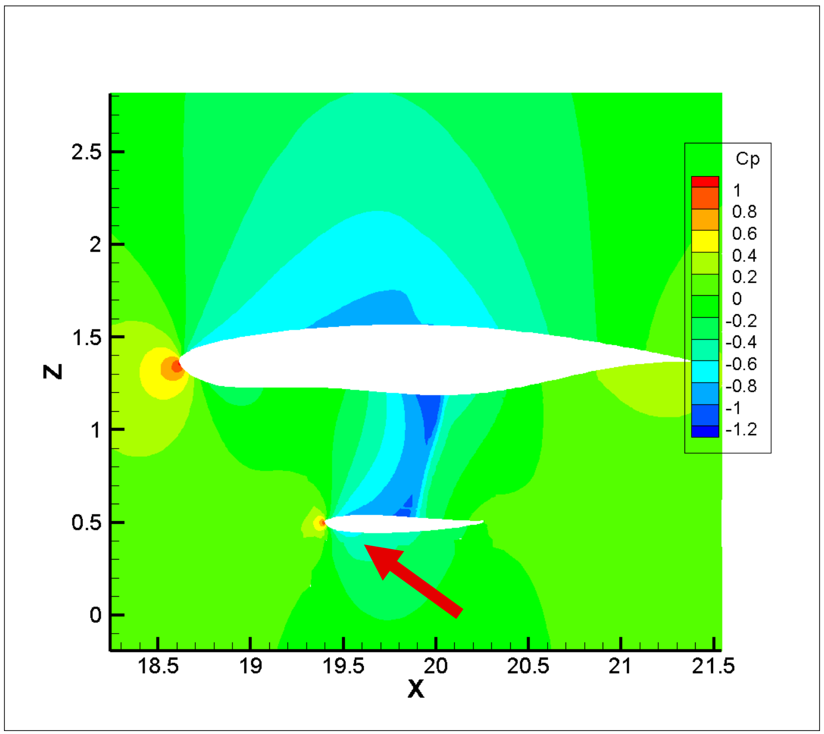
- 2D trial optimization
- Section Y=15 (Slice from 3D result)

- 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)

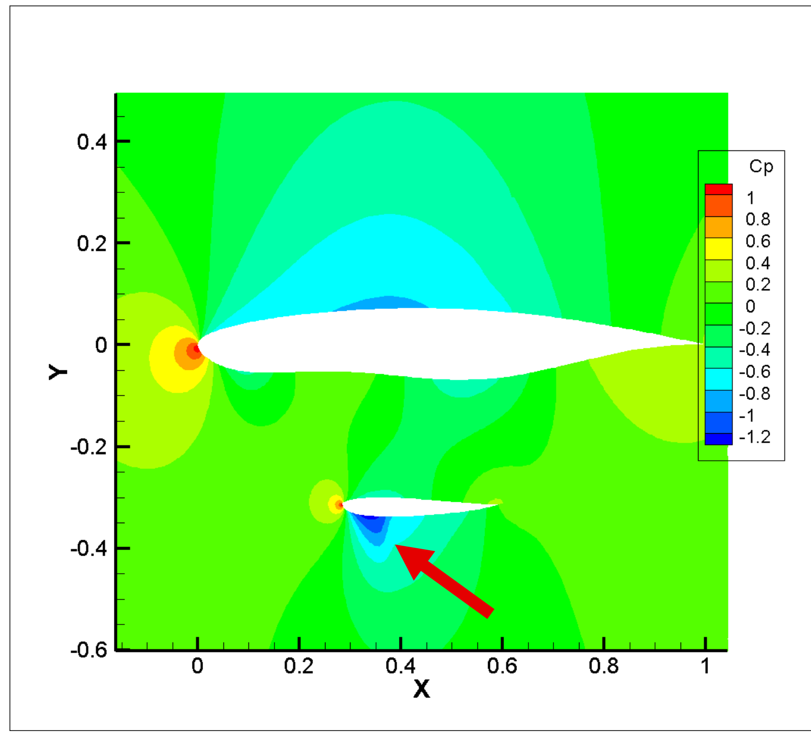


Optimization Design

- 2D trial optimization => Install to 3D configuration
- Section Y=15 (Slice from 3D result)



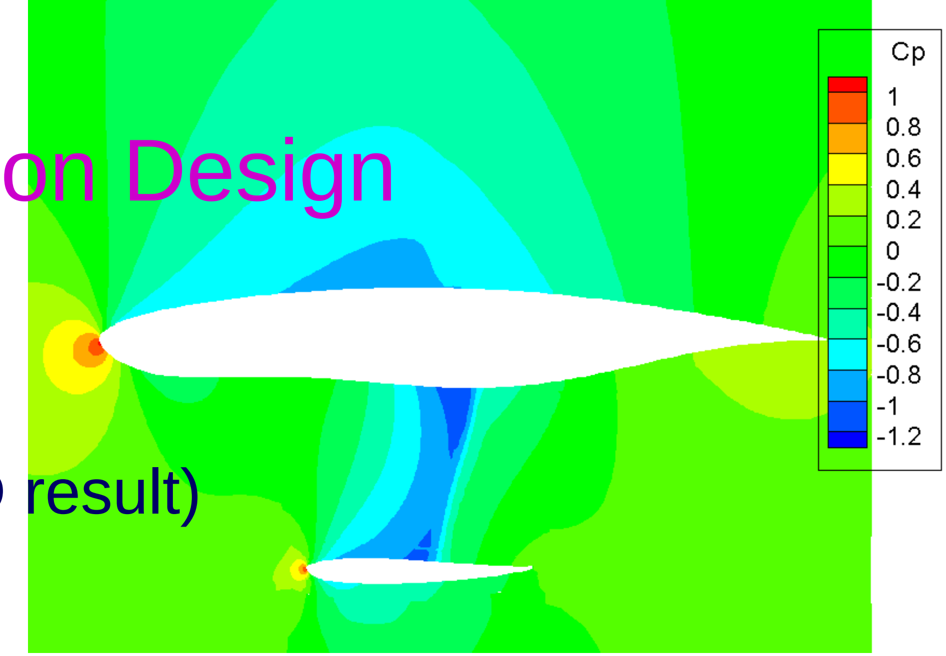
2D Optimized foil in 3D



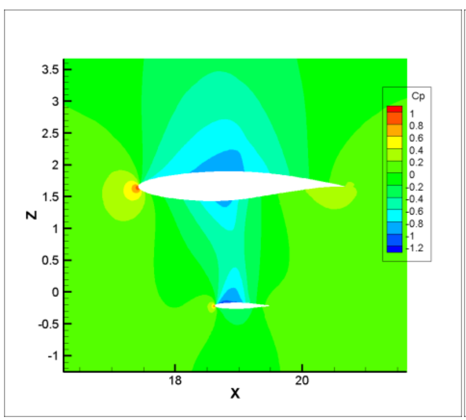
Original foil in 2D Calculation
Ma=0.7 AoA=1.03 Re=7.1mil
CL=0.3709 Cd=0.01438

Optimization Design

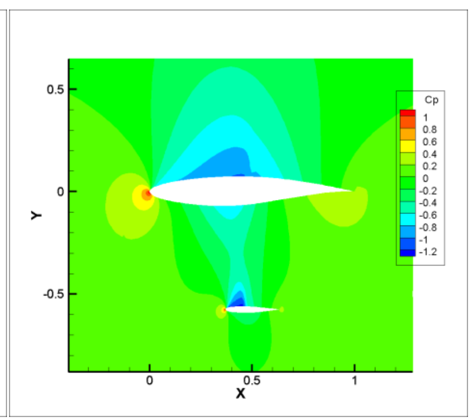
- 2D optimized foil in 3D
- Section Y=15 (Slice from 3D result)



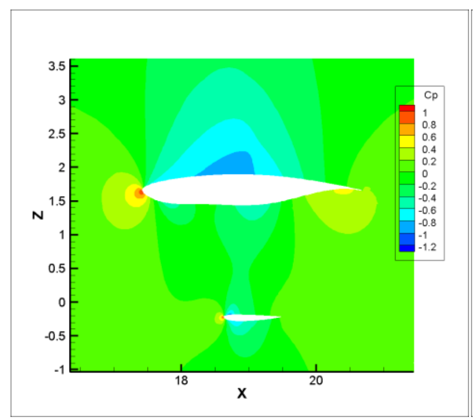
- Wave still exists, i.e. 2D ≠ 3D in the junction region
- However, when far away from the junction, 2D ~ 3D (Y=11)



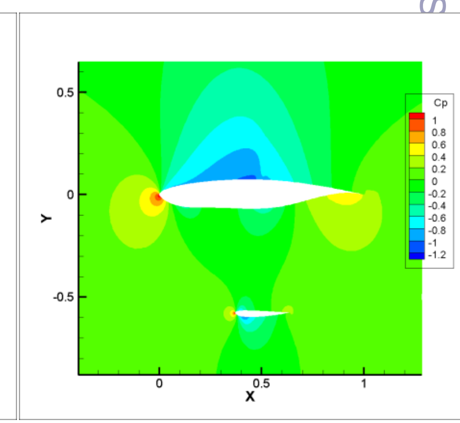
Original 3D Slice



Original foil in 2D Calculation



2D Optimized foil in 3D



2D Optimized foil

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

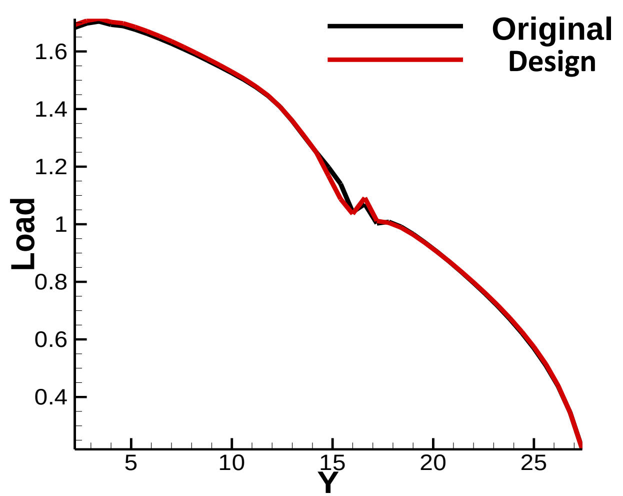
Design V.S. Original

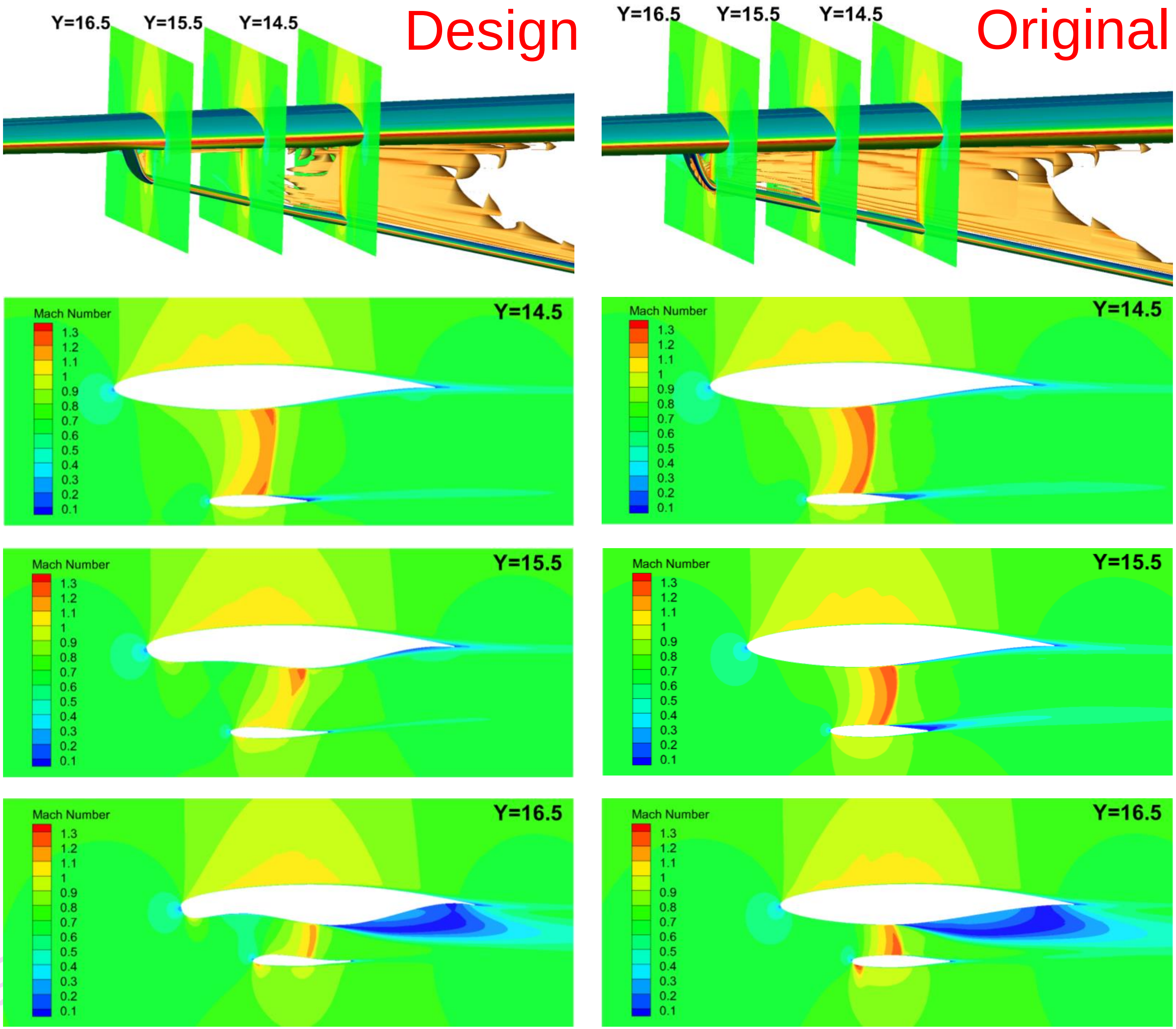
Design Result

- Final design has a total 5 count drag reduction

	Lift Coefficient	Total Drag Coefficient	Moment Coefficient
Original	0.406	0.02270	1.514
Design	0.406	0.02162	1.488

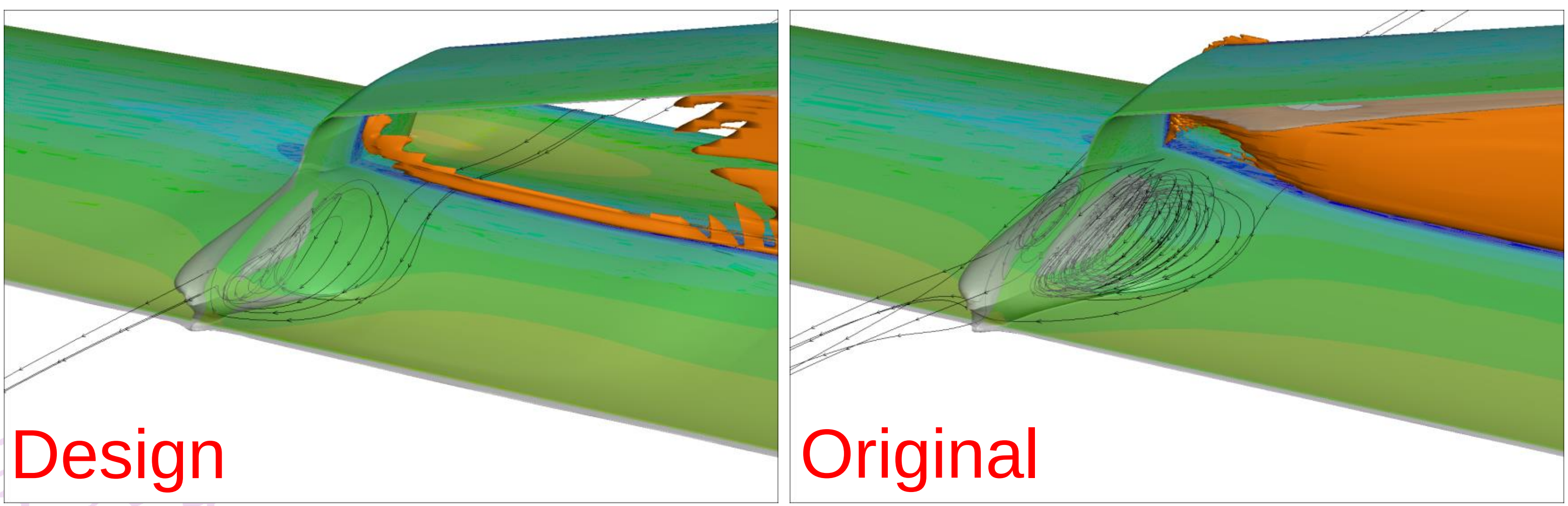
- The span load is basically kept the same




Design
Original
Y=16.5
Y=15.5
Y=14.5
Mach Number
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Y=14.5
Y=15.5
Y=16.5

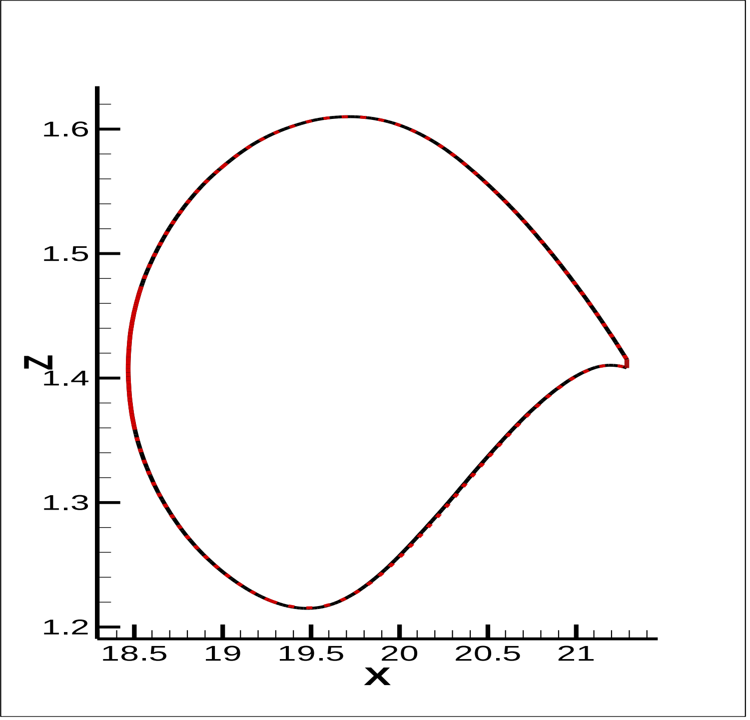
Separation Bubble

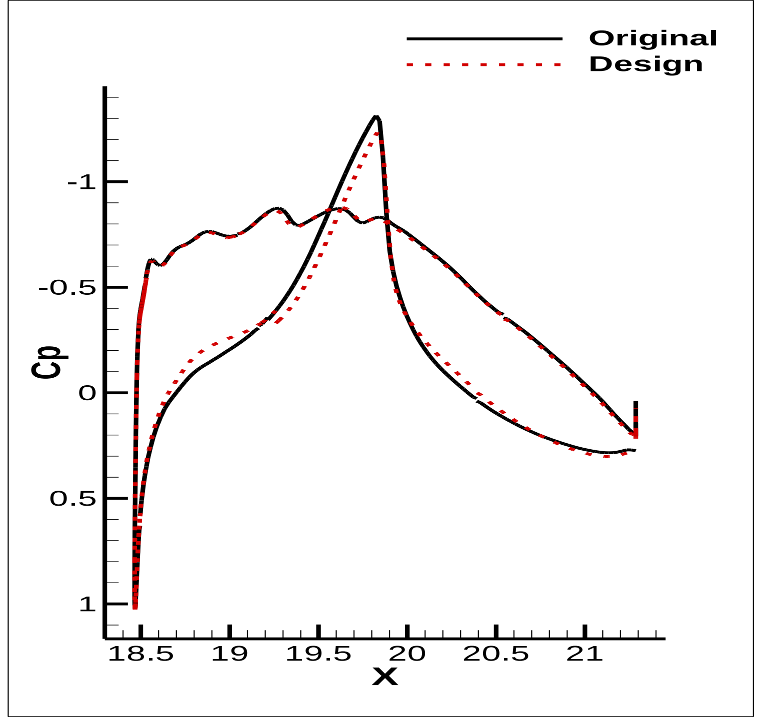
- junction region has separation
- The final design has remaining wave in the joint region, along with the wall interference, causes the separation not significantly reduced
- Iso-surface (gray) is defined by Ma=0.2



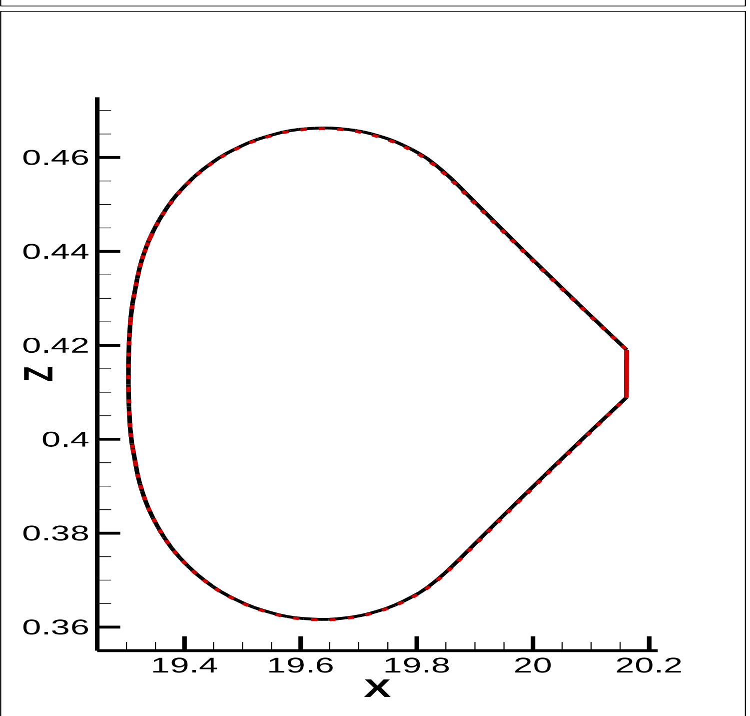
Y=14.5

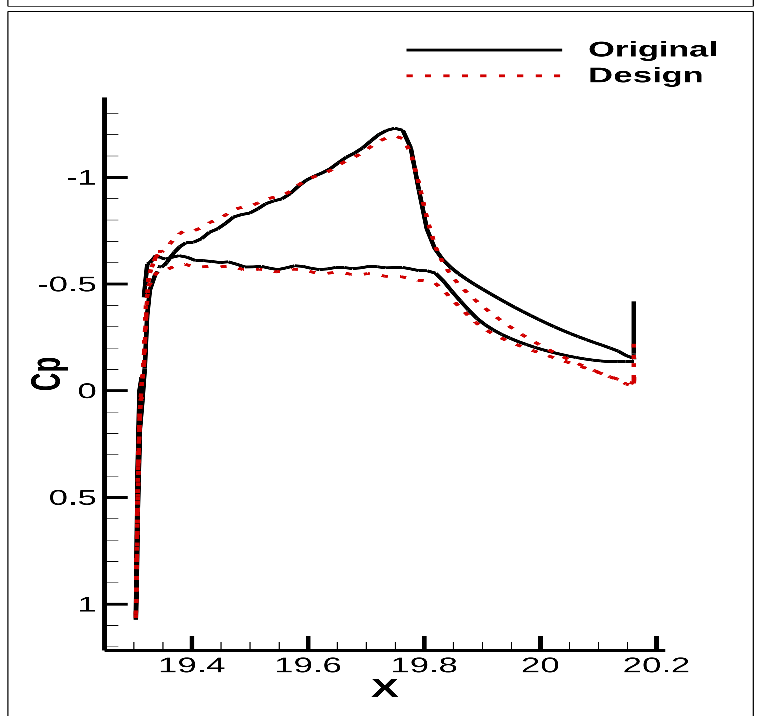
Foil Unchanged





Wing





Strut

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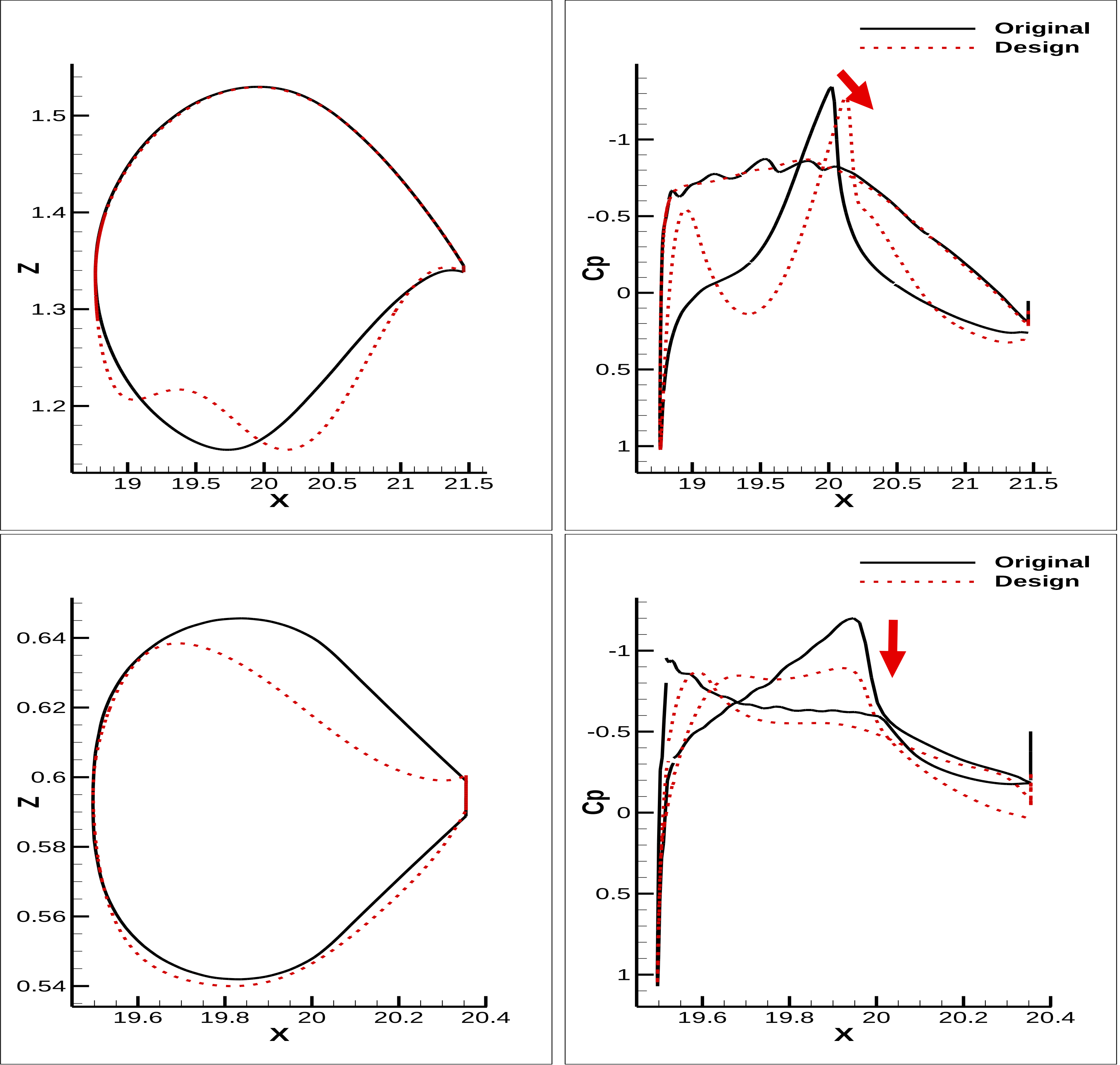
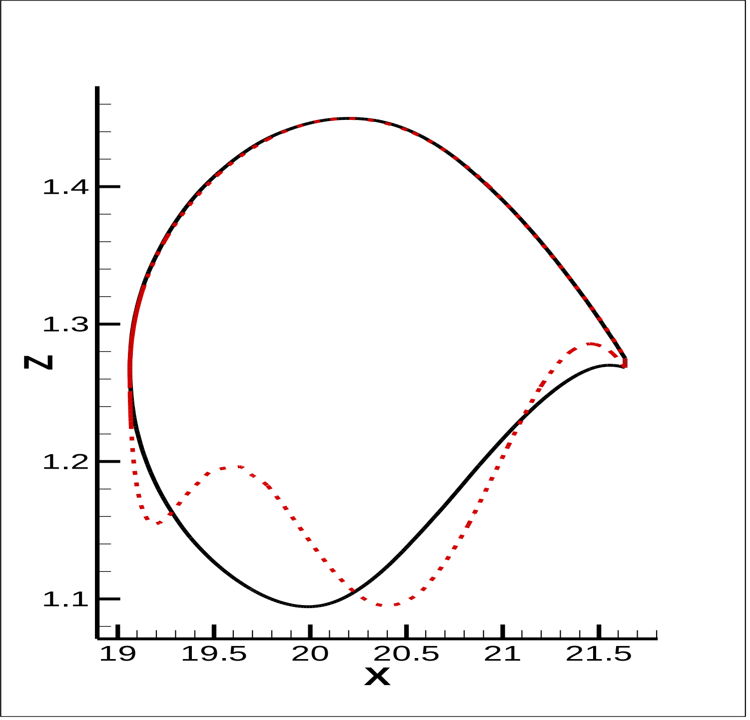
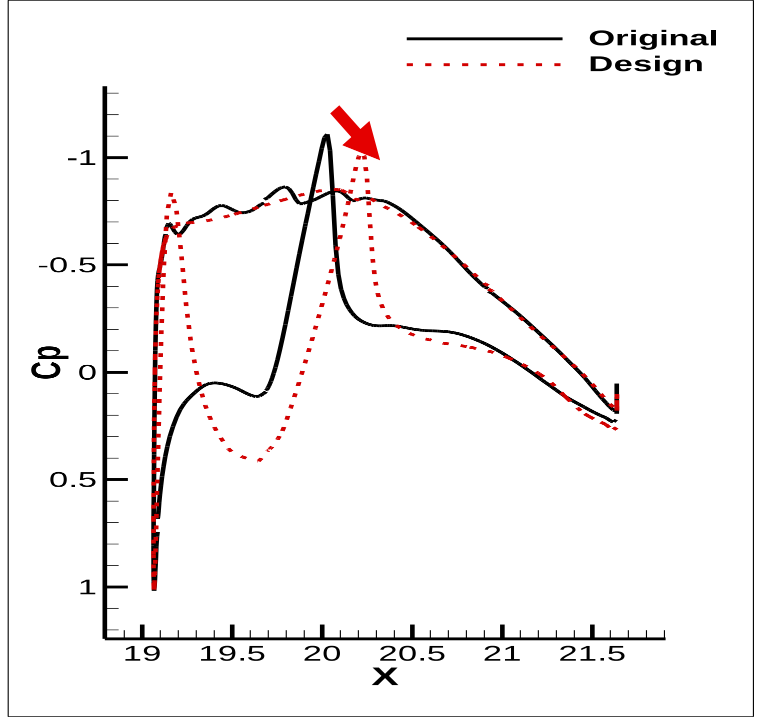


Y=15.5

Wing

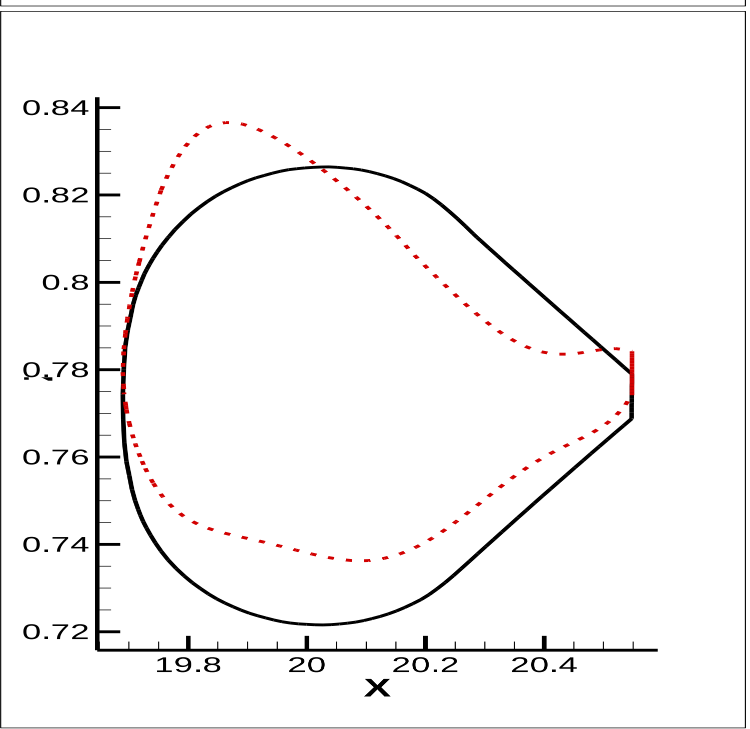
Strut

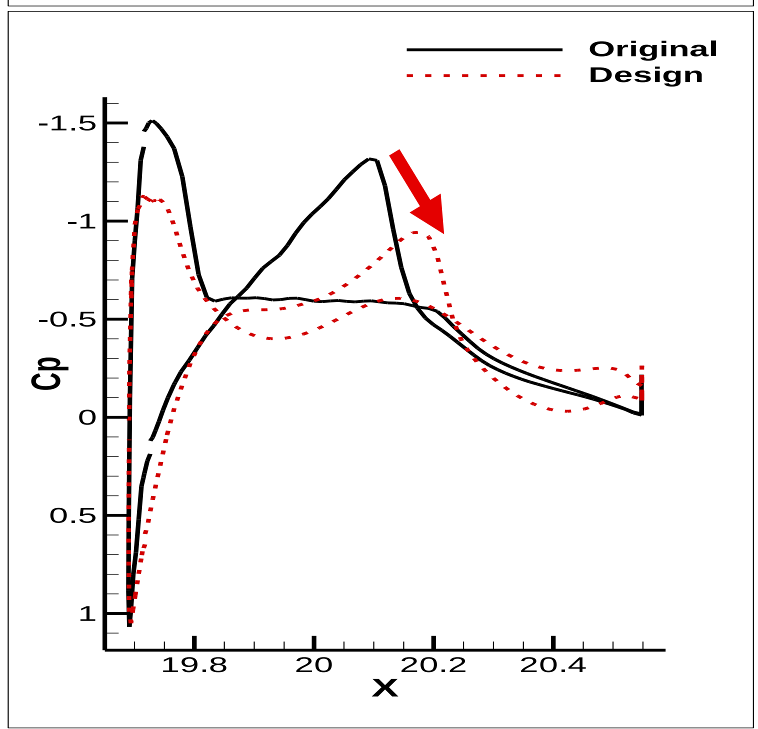




Y=16.5

Wing

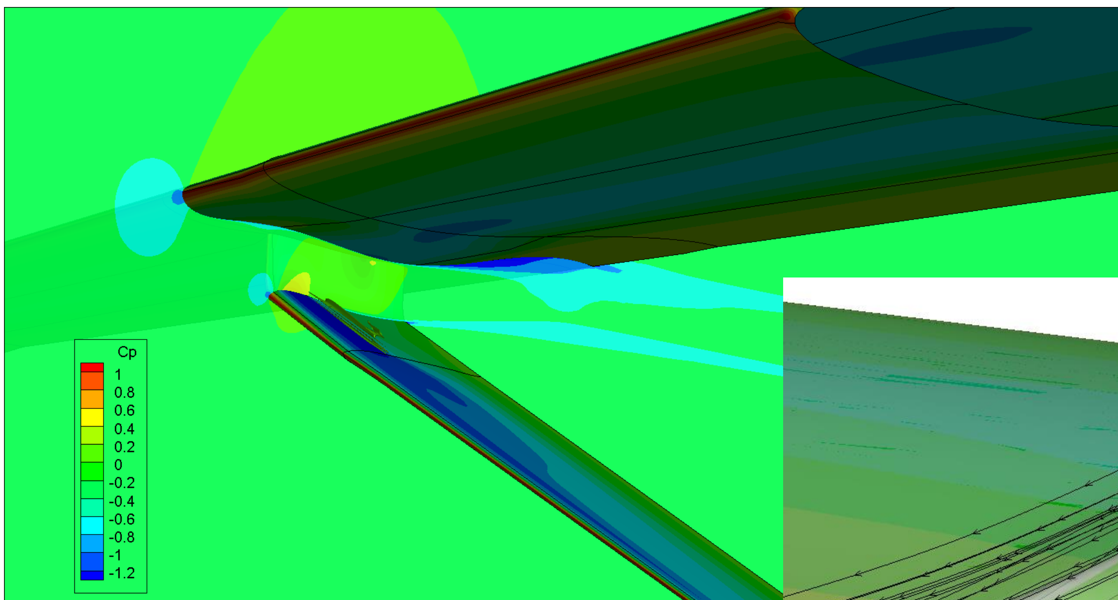


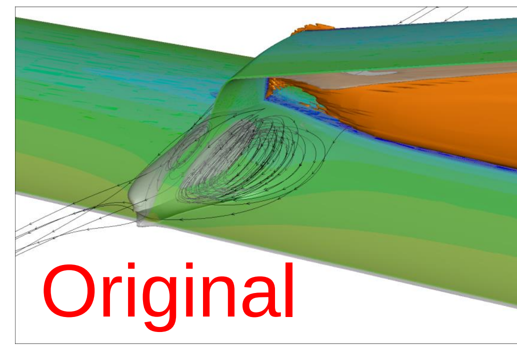


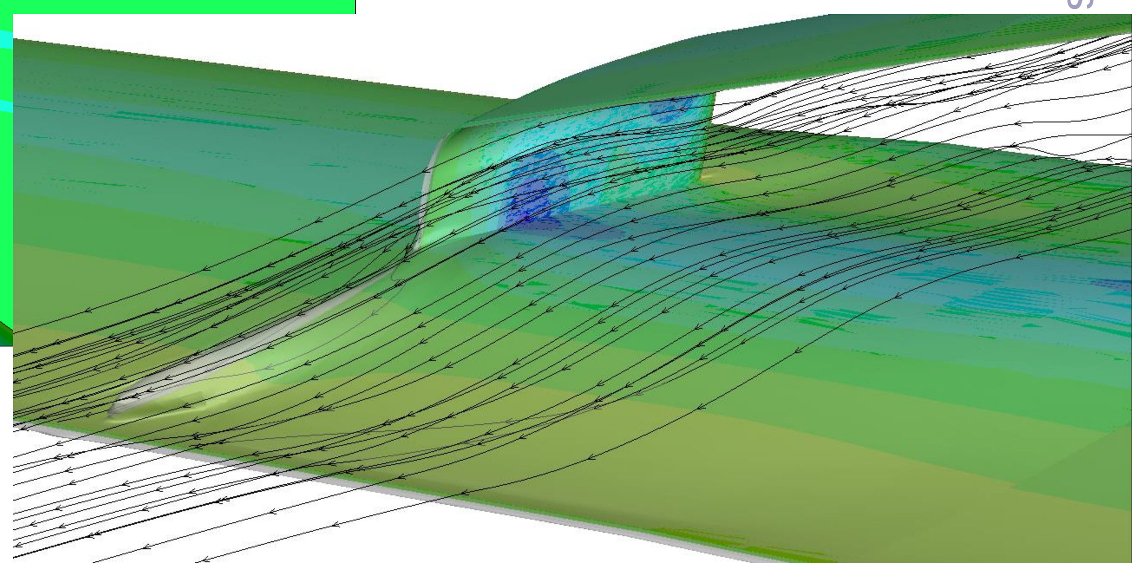
Strut

Off-Design Performance

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

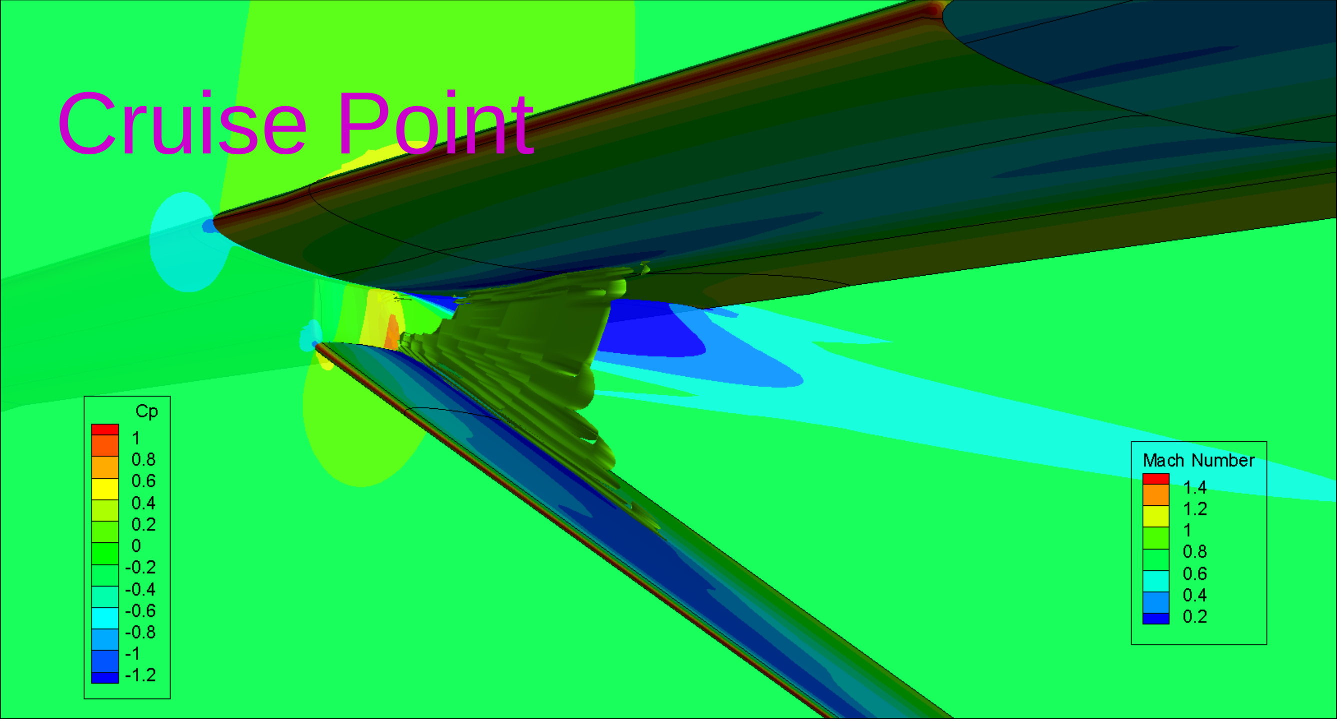






Ma=0.68 AoA=1.0deg

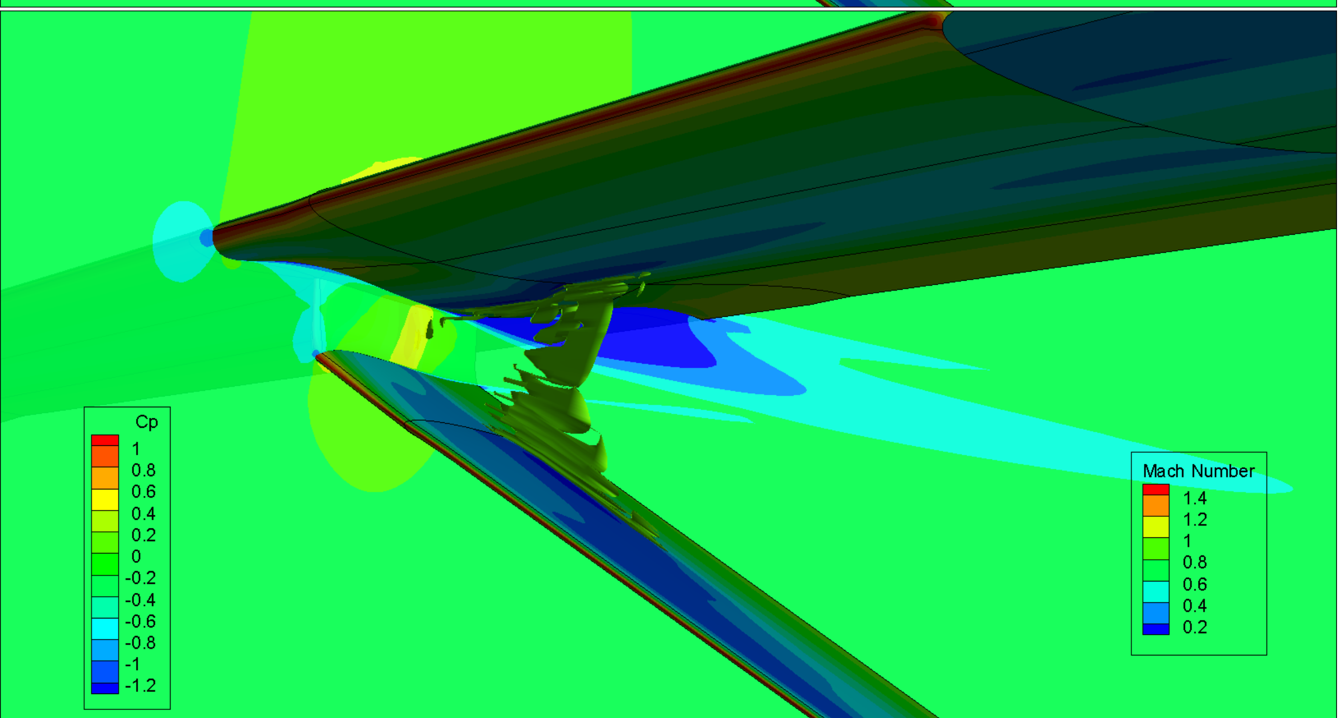
Original



Ma=0.72

AoA=1deg

Design

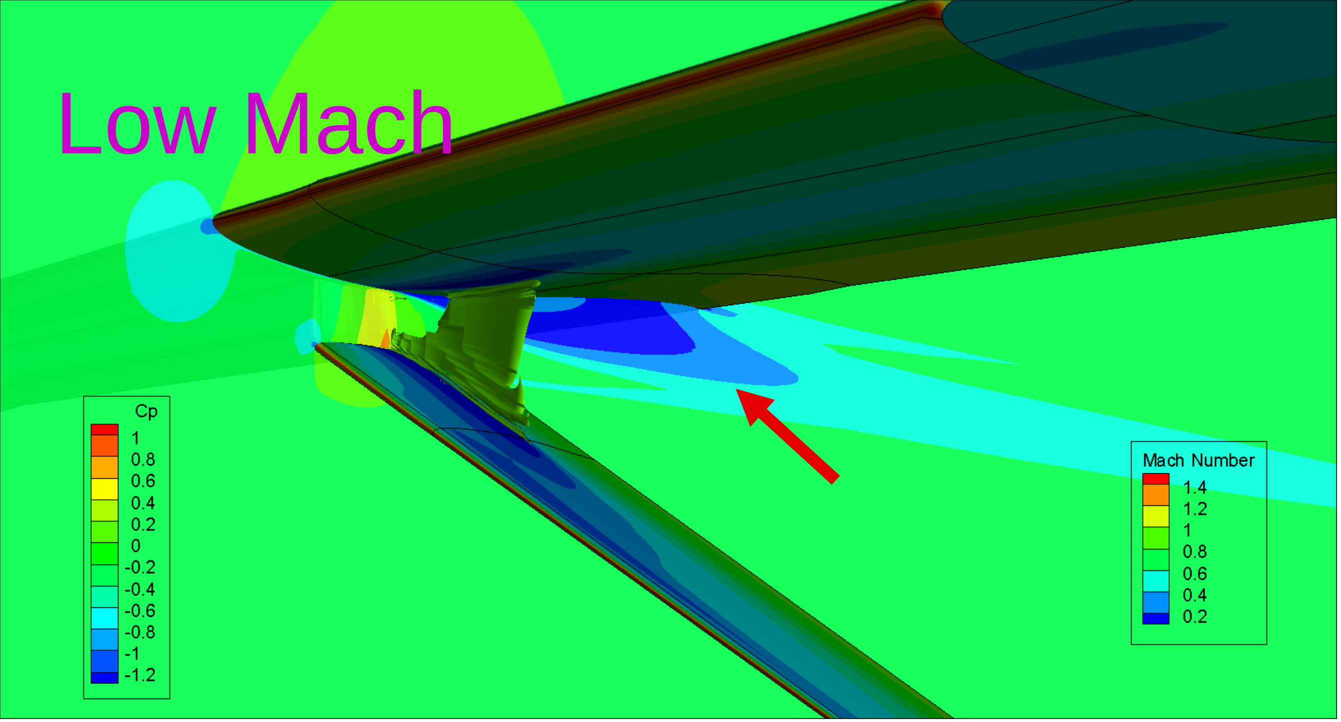


Slice Contour: Mach

Surface Contour: Cp

Iso-surface: wave_flag=1.1

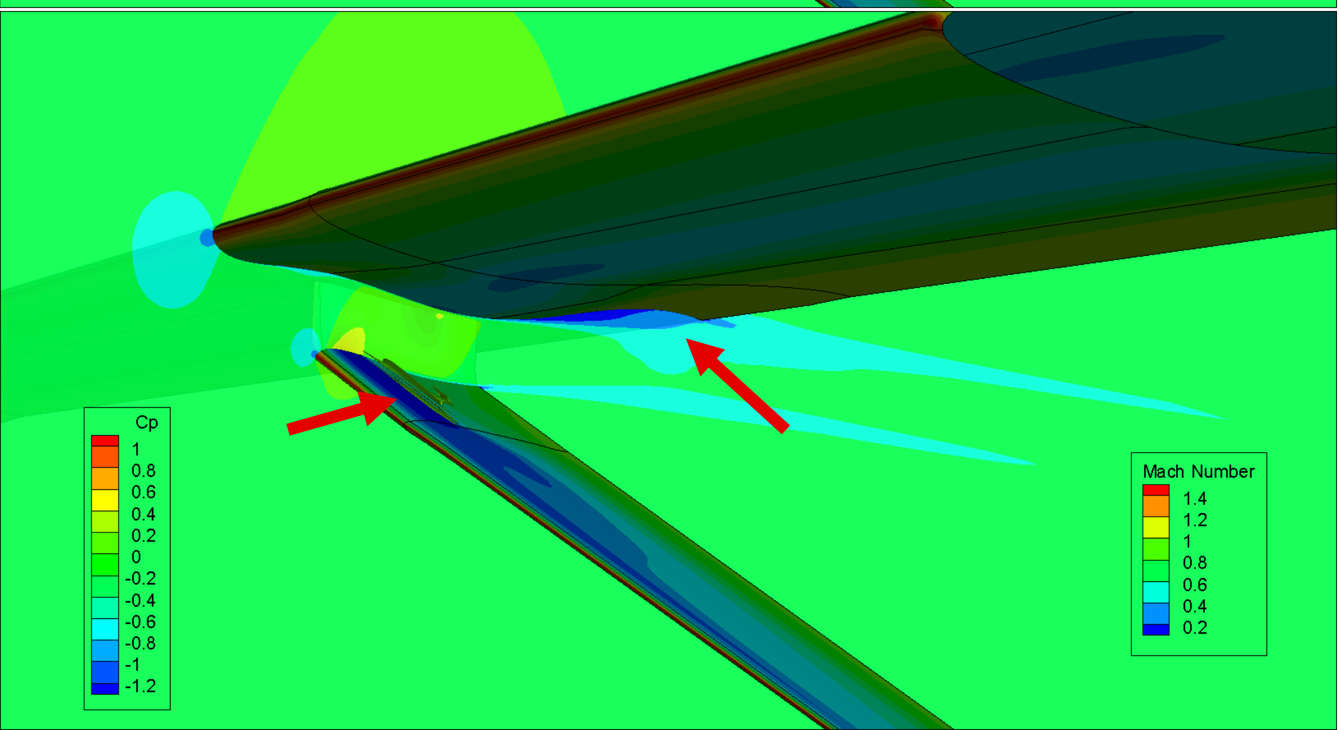
Original



Ma=0.68

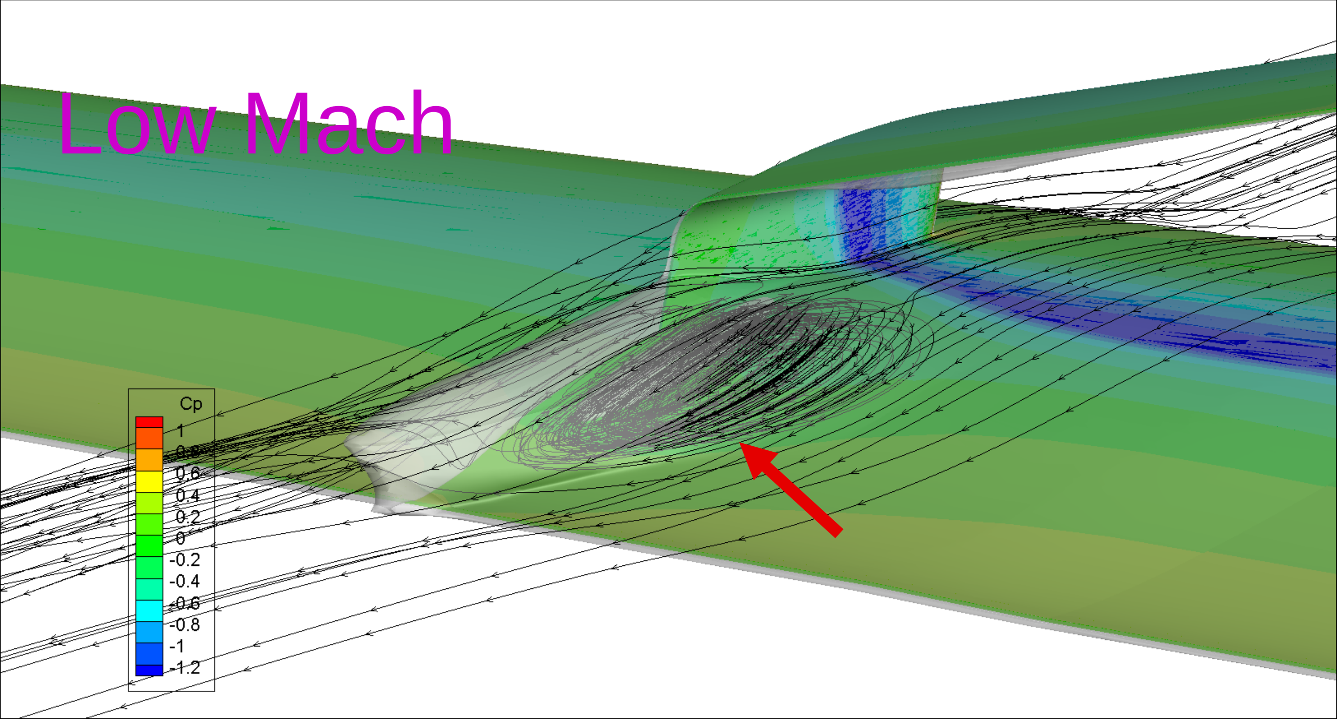
AoA=1deg

Design



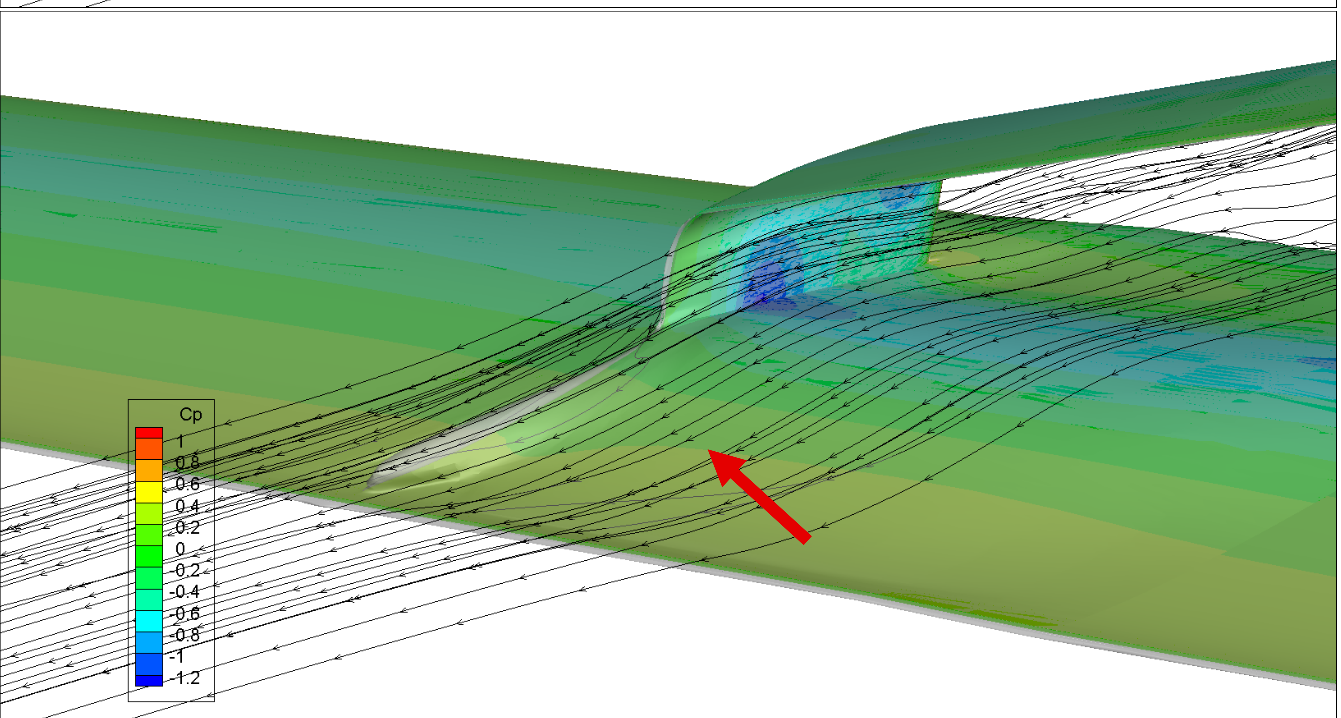
Slice Contour: Mach
Surface Contour: Cp
Iso-surface: wave_flag=1.1

Original



Ma=0.68
AoA=1deg

Design



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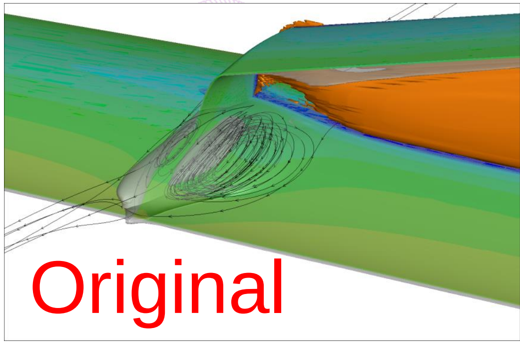
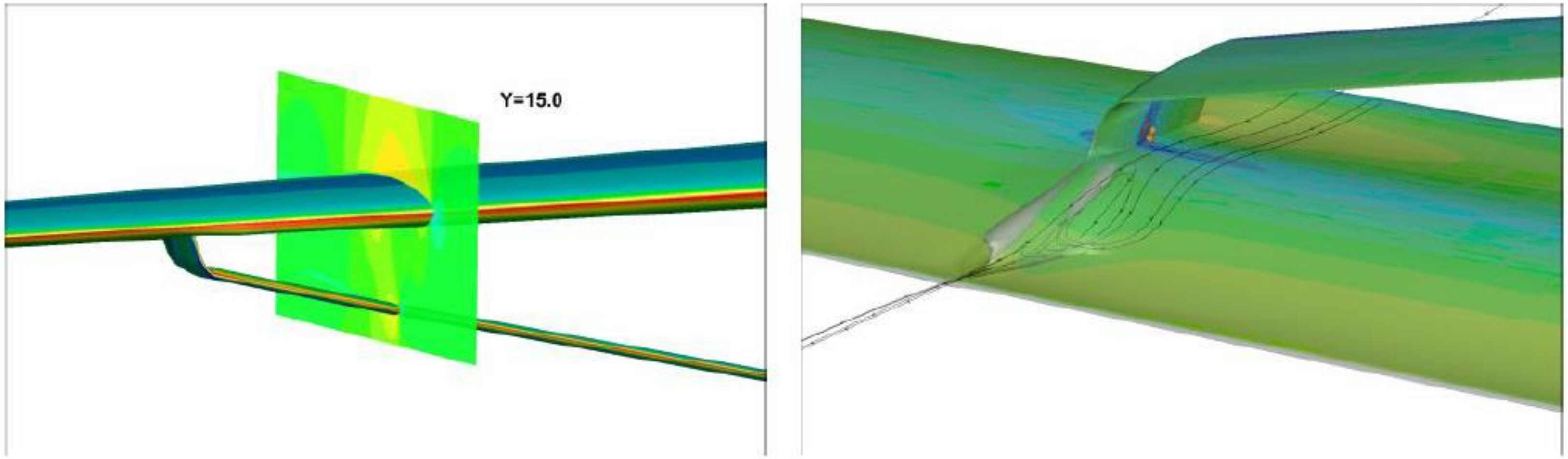
Surface Contour: Cp
Iso-surface: Mach=0.2

Further Modification

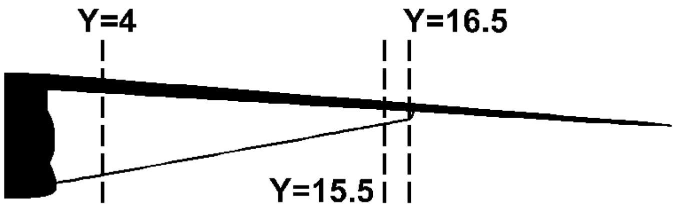


- Expand the modification region to Y=11~17
- The remaining wave and separation can be further reduced
- (Previously Y=15~17)

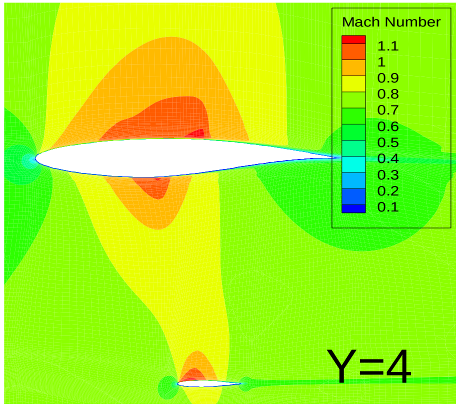


(1) Shock Wave (2) Separation

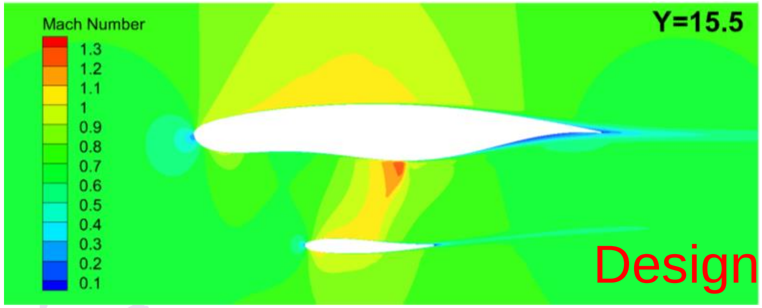
Figure 4 Shock Wave of a Further Design (Design Region: Y=11 to Y=17)

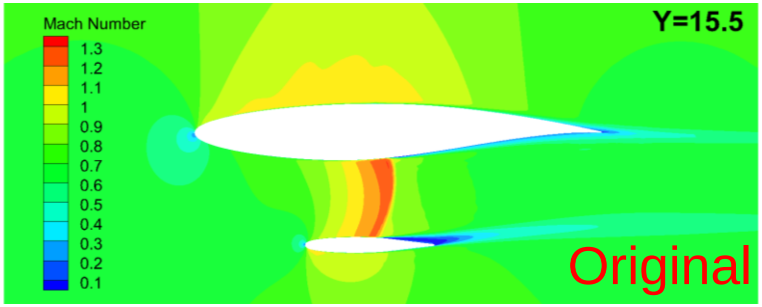


Conclusion



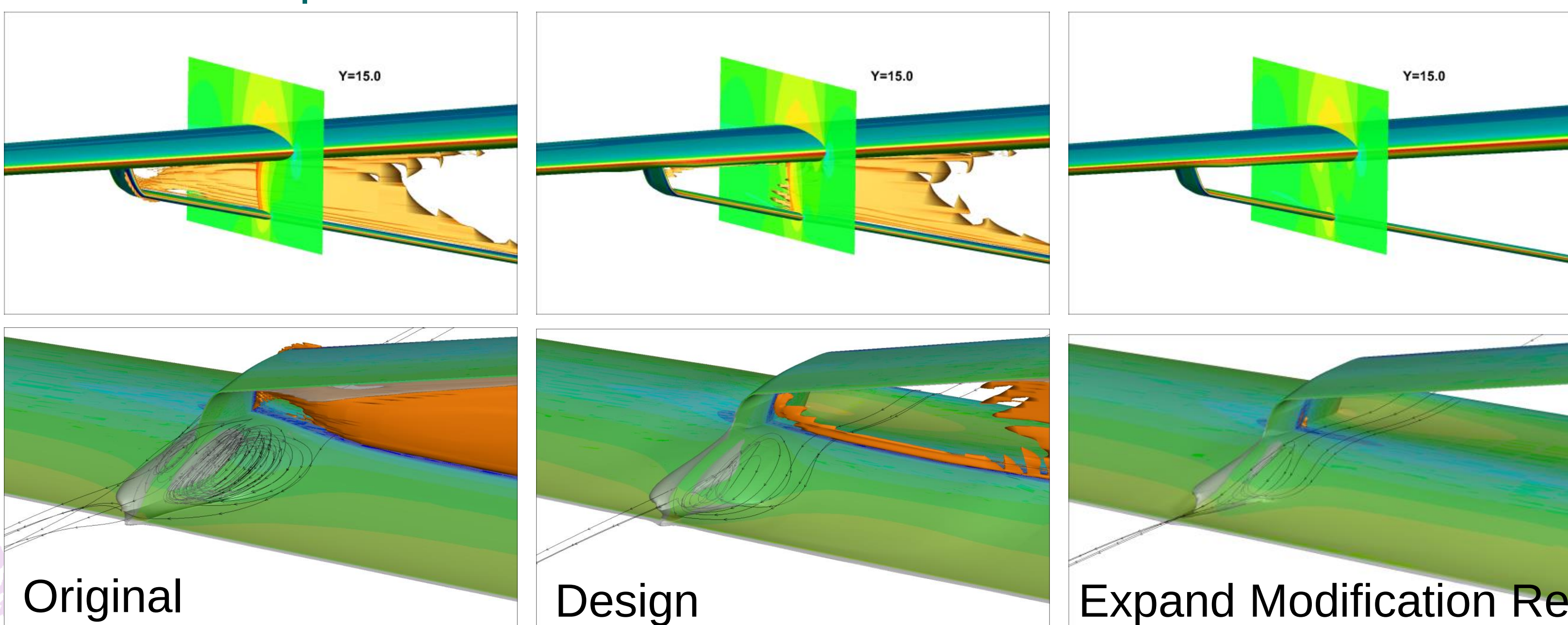
- The interference between wing and strut
  - Not negligible even when they are relatively far away (Y=4)
  - Junction region acting like a nozzle, causes strong wave
  - Separation exists
- Geometry modification
  - Basic idea is modifying the “nozzle” streamwise area distribution
  - Avoid flow acceleration between wing lower surface and strut upper surface





Conclusion

- Geometry modification can reduce wave
  - Most wave within the modification region (Y=15~17) 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



Original

Design

Expand Modification Region

Thank You

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Runze LI

2017.11.29