# Investigations of passive flow control devices for wave drag reduction

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INCAS
National Institute for Aerospace Research "Elie Carafoli"

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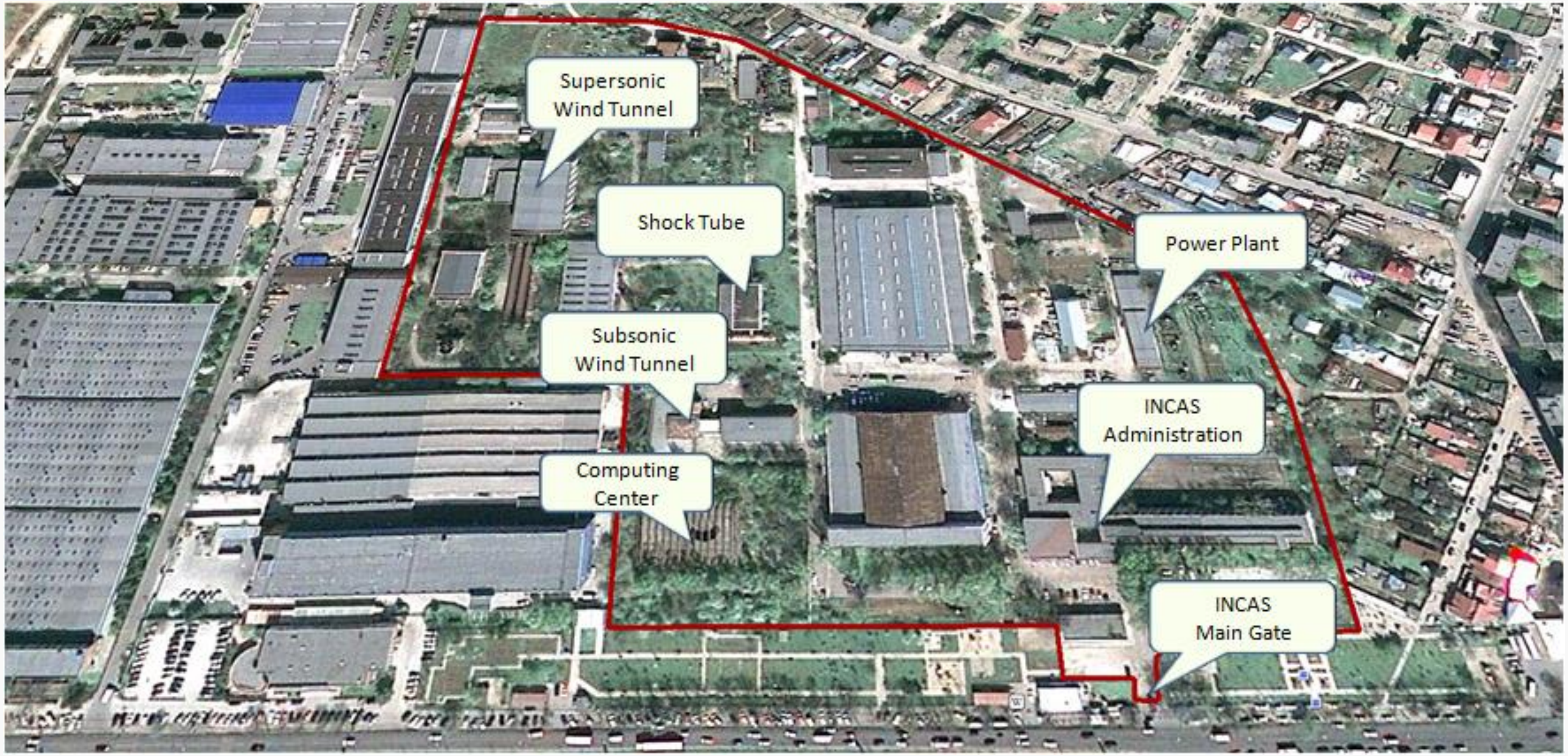
# INCAS presentation




Main Location : Bucharest, Iuliu Maniu 220
Secondary Location : Maneciu, Prahova district
New Location(s) for special activities

# INCAS presentation

National Institute for Aerospace Research "Elie Carafoli"

Profile :

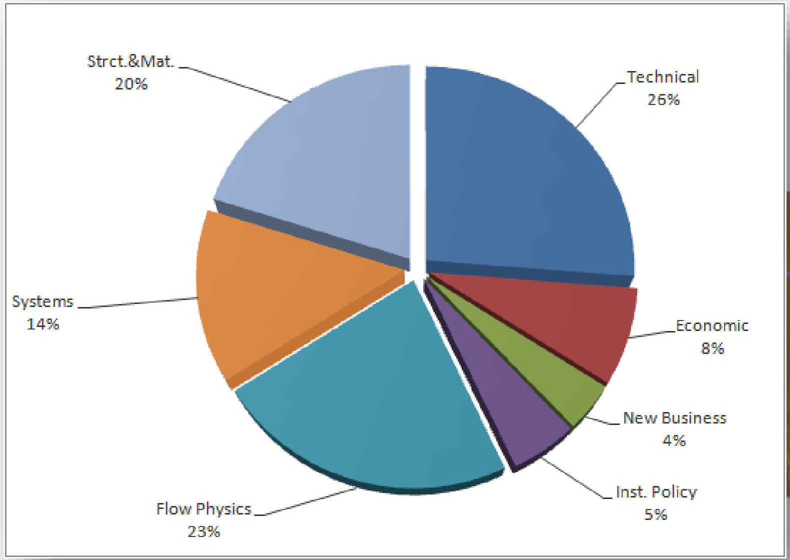
- ➢ State owned company/ Public body
- ➢ Founded in 1949
- ➢Leading research establishment for aerospace research in Romania

Major activities :

- ✓ Main design authority and system integrator in aeronautics
- ✓ Aerodynamic design
- ✓ Structural design and analysis
- ✓ Experimental wind tunnel validation
- ✓ Global performance analysis

- ✓ Atmospheric investigations
- ✓ Earth Observation

- ❖ Research and development in aeronautics and aerospace sciences



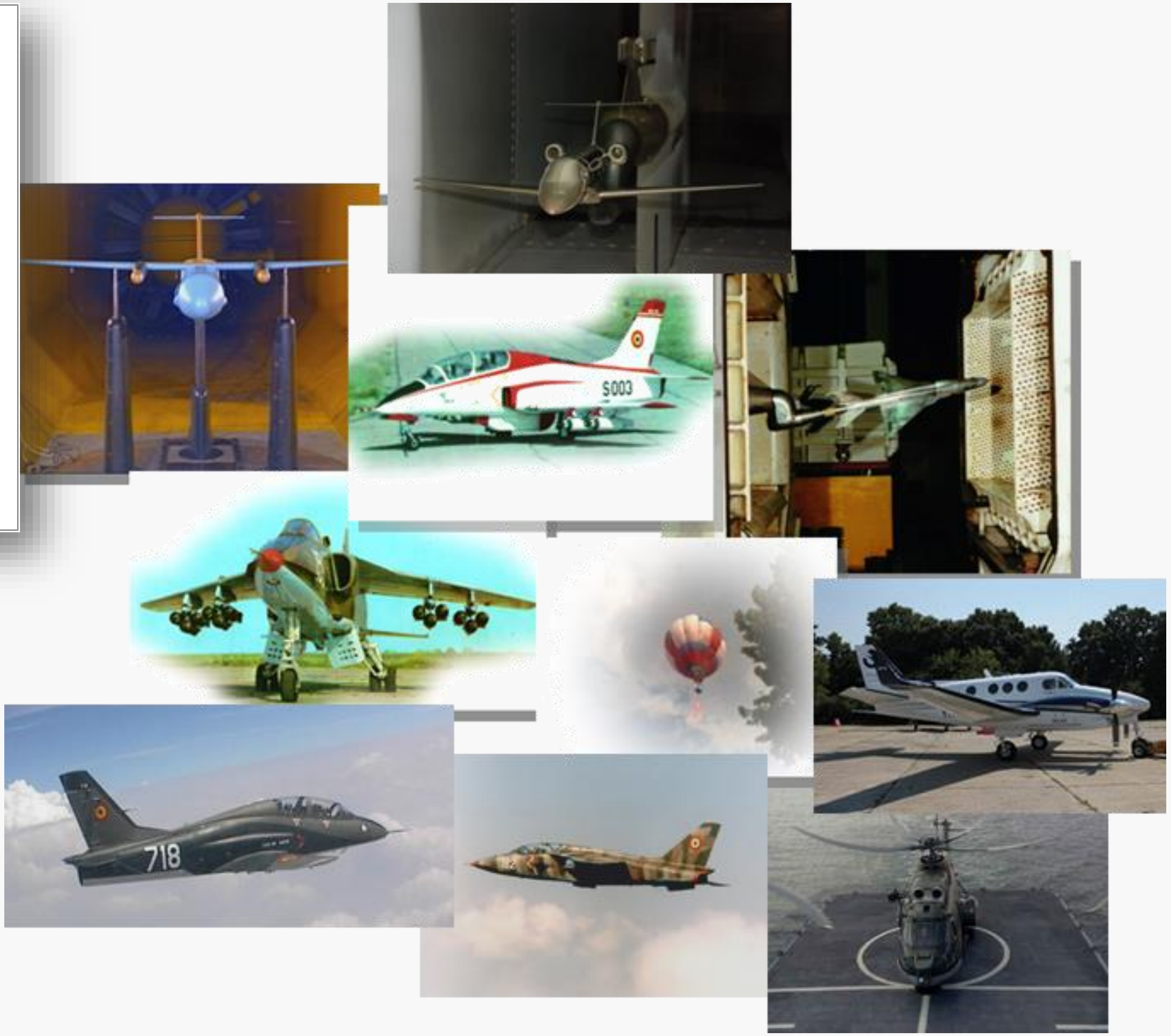

INCAS Personnel Structure

Total positions - 218
R&D positions – 126

Total researchers – 106
Where :

PhD – 21
PhD students – 14

PhD leaders - 3



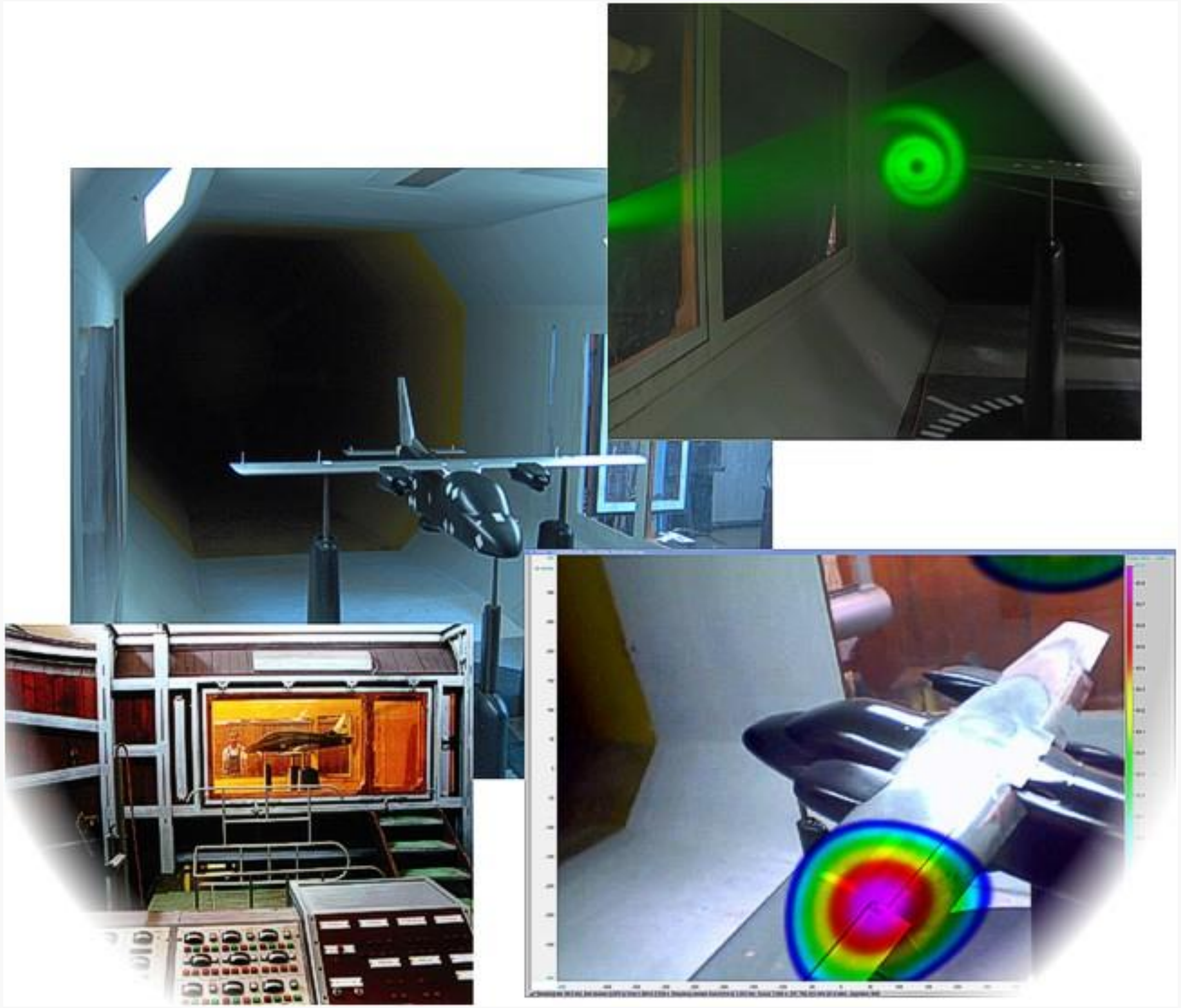
# INCAS presentation

***Subsonic Wind Tunnel***

- Atmospheric pressure, continuous type facility
- Maximum speed : 110 m/s
- 2.5m x 2.0m x 4m test section
- Usual Reynolds number up to 1.5 million.

***Equipment:***

- Traditional closed circuit type
- Solid walls test section
- External 6 component pyramidal type balance
- Standard pressure acquisition systems
- New data acquisition technologies
  - Hot film/wire measurements
  - IR camera
  - PIV system
  - 3D dynamic deformation – fast cameras
- Laser visualization systems
- CTS system – open/closed loop operation
- Aeroacoustics and airframe noise evaluation
  - 72 microphone matrix system
  - Beamforming technology
  - Cross-corelation with dynamic pressure/kulites



# INCAS presentation

***Supersonic Wind Tunnel***

• blowdown type
• 1.2m x 1.2m test sections (3D)
• Mach number range :  0.1 … 3.5
• Reynolds number up to 100 millions/m
• Max test run duration : 90 sec.
• Max pressure : 16 bar (settling chamber)

• Interchangeable porous transonic test section
• Variable porosity from 0.01% up to 9%
• Interchangeable complex 3D/2D 0.8m x 1.2m test section
• Active model/combustion capability

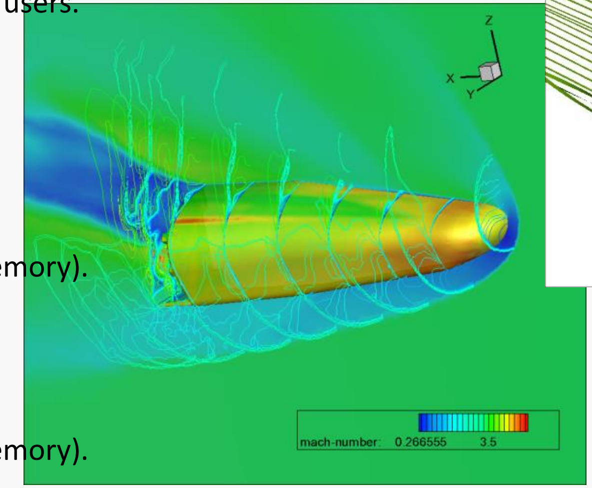
***Equipment:***

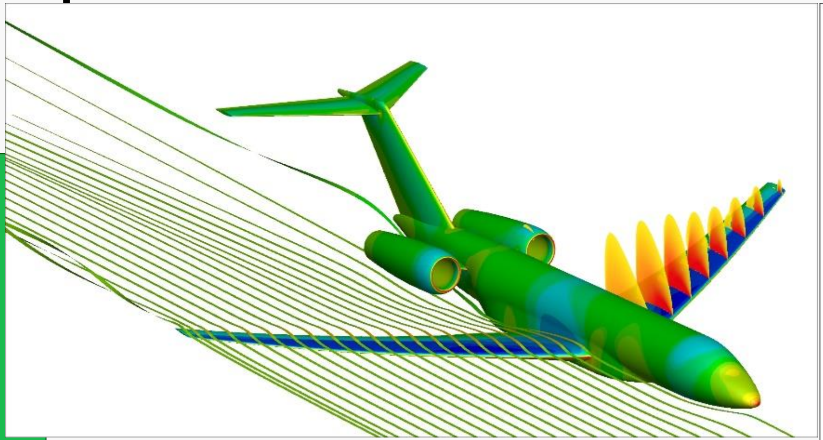
• Sting mounted, internal balance
•Pressure measurements
•Mach control system
• CTS system
• 800 mm schlieren system
• PIV under development
• IR camera
• ultra fast digital camera

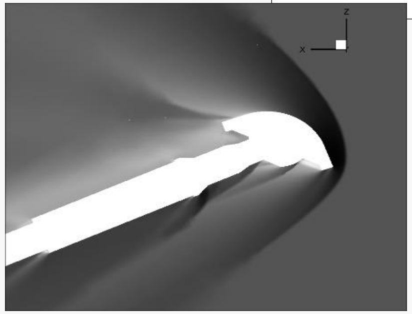
CFD Lab

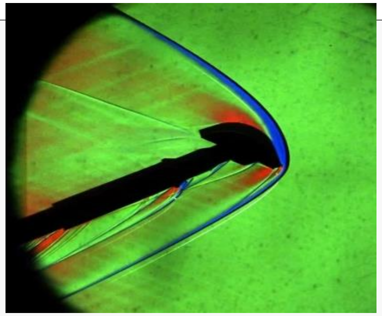
# INCAS presentation

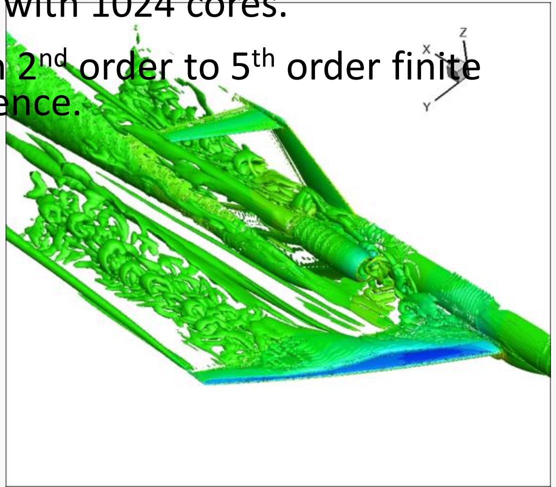
- SGI UV-2000 :
  - 528 cores (Intel Xeon E5-4627v2)
  - 8.4 TB RAM (shared memory)
  - 42 TB for storage / 30 TB for users.
  - 12 Intel Phi
  - 4 NVidia Quadro 6000
  - Linux - SuSe.
- SuperMicro:
  - 160 cores
  - 320 GB RAM (distributed memory).
  - Windows.
- Beowulf:
  - 48 cores
  - 512 GB RAM (distributed memory).
  - Windows.
- Ansys Fluent and CFX with 272 cores.
- Numeca Fine/OPEN with 1024 cores.
- In-house codes from 2nd order to 5th order finite volume/finite difference.

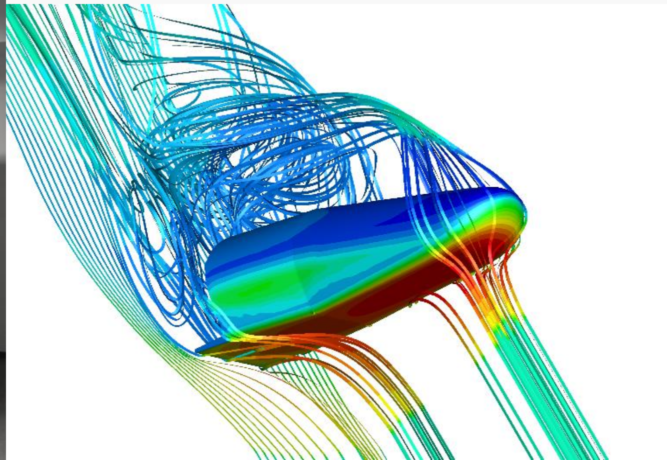






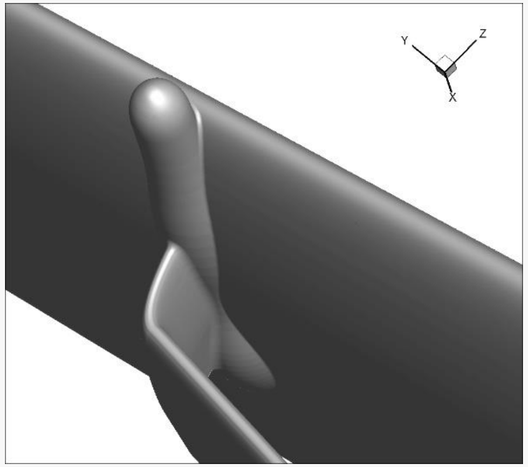




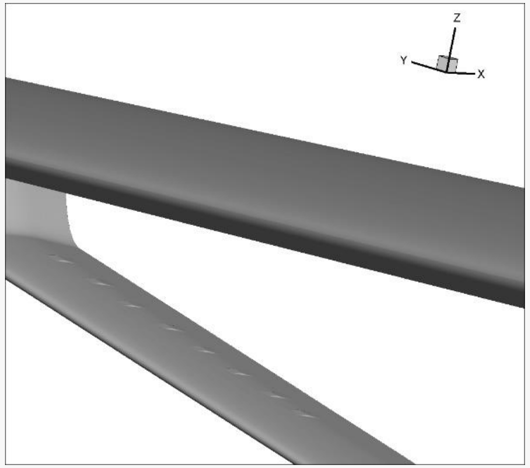
# Introduction

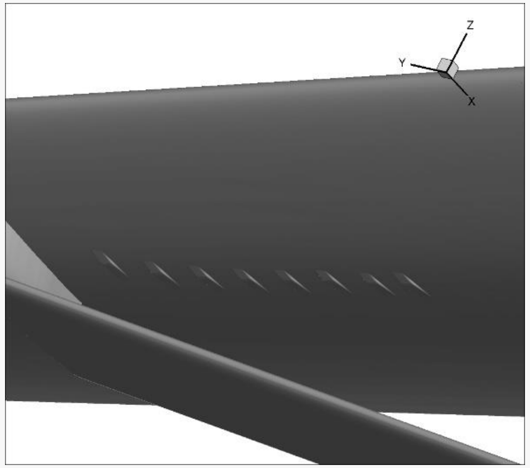
Three methods for reducing the drag associated with the presence of strong shocks have been investigated:

1. Kuchemann’s Carrot

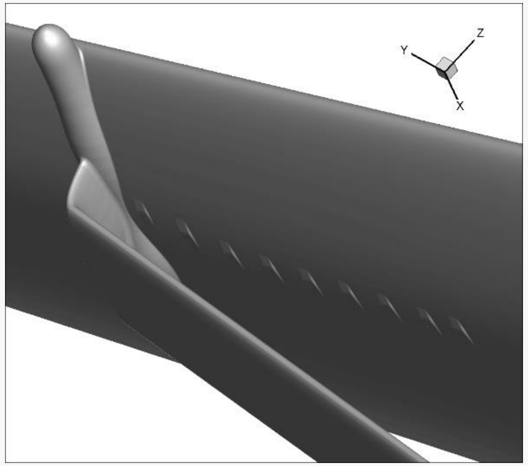


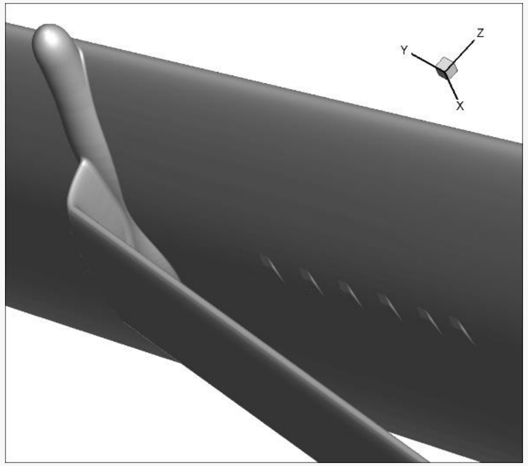
2. Shock Control Bumps

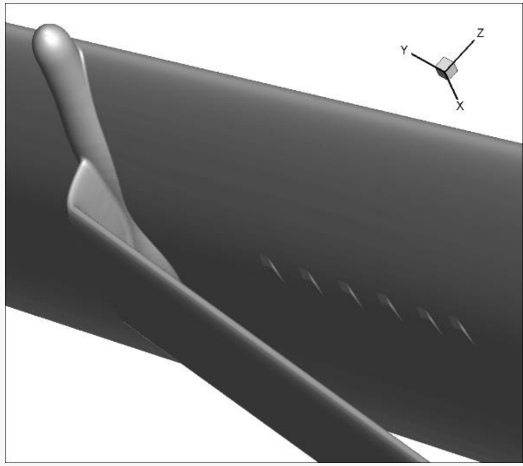




3. KC + SCB ( v0, v1 ,v2)





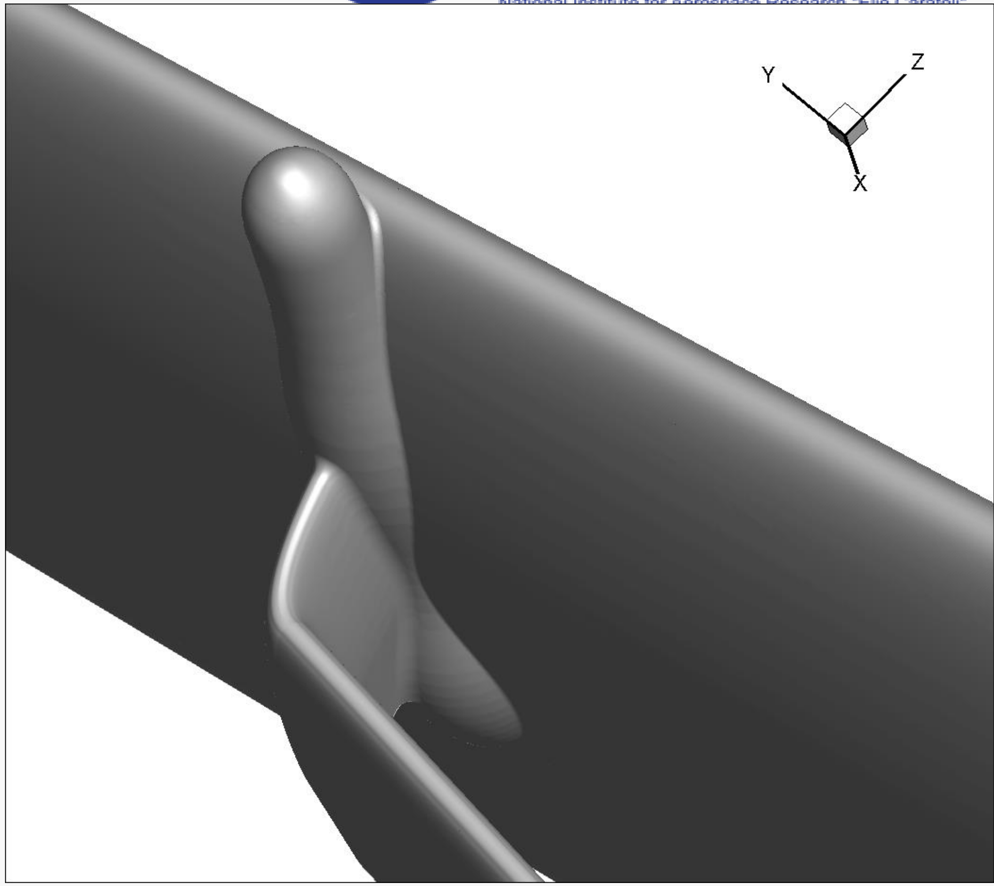


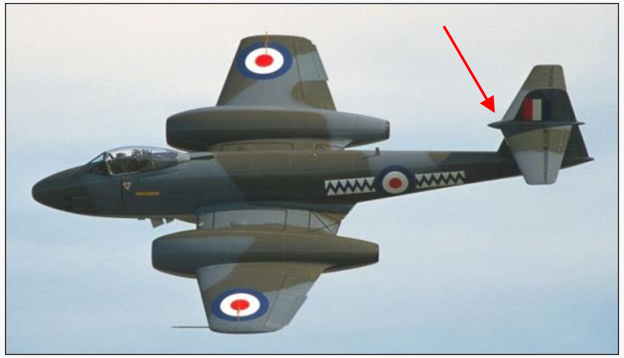
# Introduction

**Kuchemann's Carrot**:

- Positioned at the wing-strut junction – Local effect
- Below the wing's leading edge not to affect the suction side
- "Fuselage-waisting" at the strut's maximum thickness
- Improves the "area-rule"
- Used on a number of aircrafts from the past:
  - ✓ Tu 134
  - ✓ Hawker Sea Hawk
  - ✓ Blackburn Buccaneer
  - ✓ Gloster Meteor

- No numerical optimization used

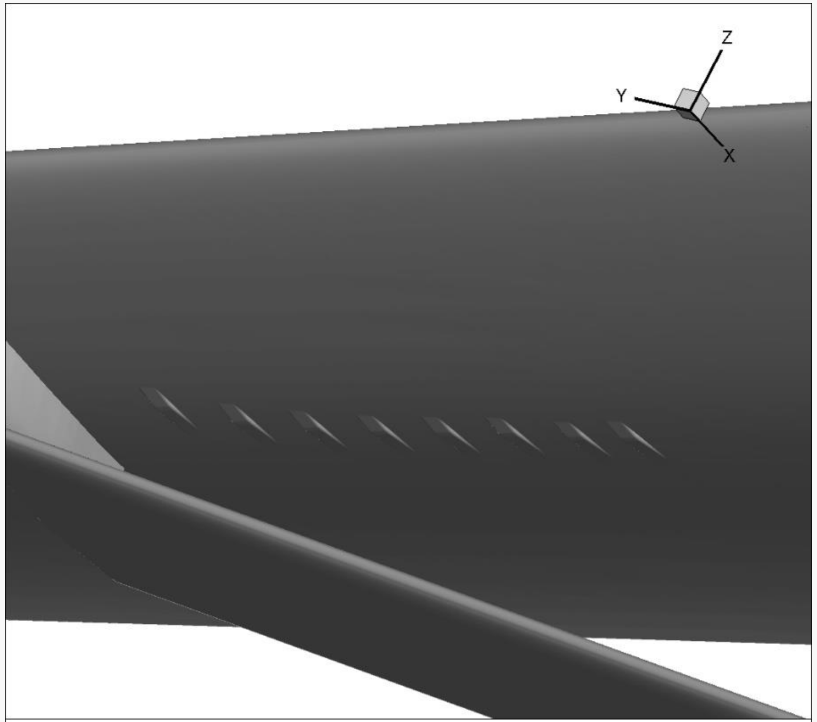


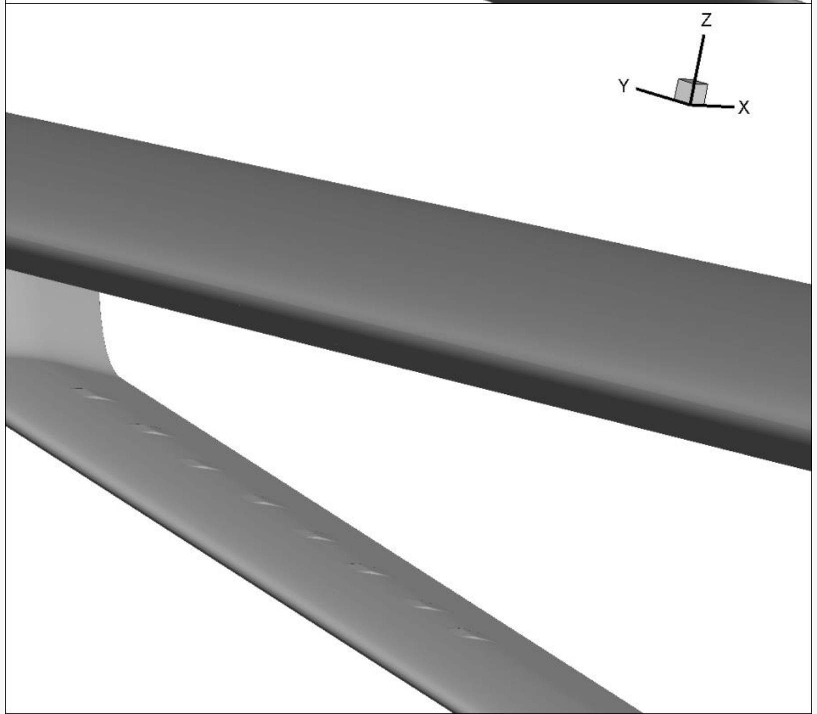



# Introduction

**Shock Control Bumps**:

- Positioned on the wing's pressure side and the strut's suction side, placed at 0.25m distance from each other – Distributed effect
- Not on the vertical strut
- Generally they have been observed to reduce drag in transonic flows where Mach number exceeds 1.3 – applicable in this case
- 3D wedge type geometry with rounded sides
- Height on the wing is roughly 70% of the boundary layer thickness
- Height on the strut is around 95%.
- The height of the bump is determined from 2D analyses at three span wise locations of 15, 15.5 and 16m
- Extended tail, flat top, a width to height ratio of approx. 9 and a length to width ratio of 4
- No numerical optimization used
- "Review of research into shock control bumps" - Shock Waves- 2015, P. J. K. Bruce · S. P. Colliss

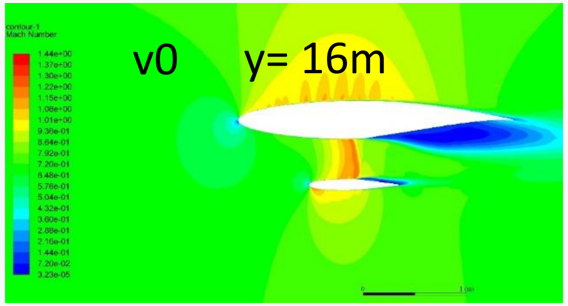


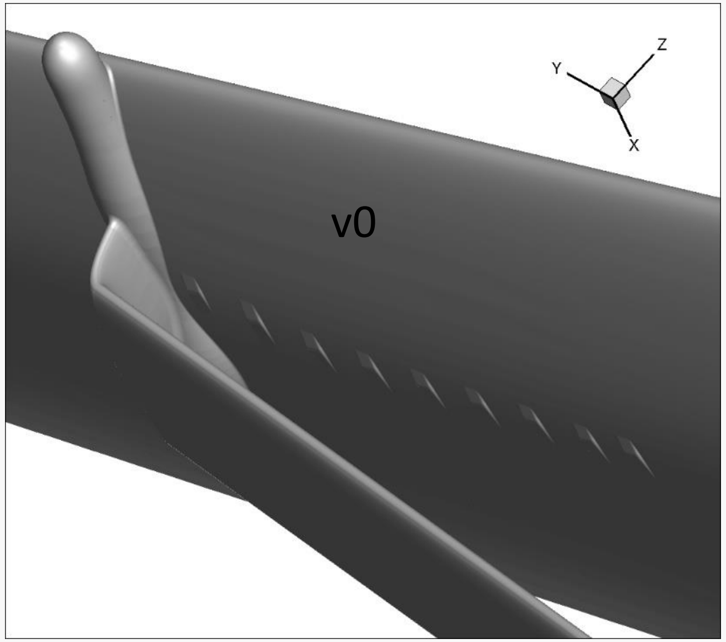



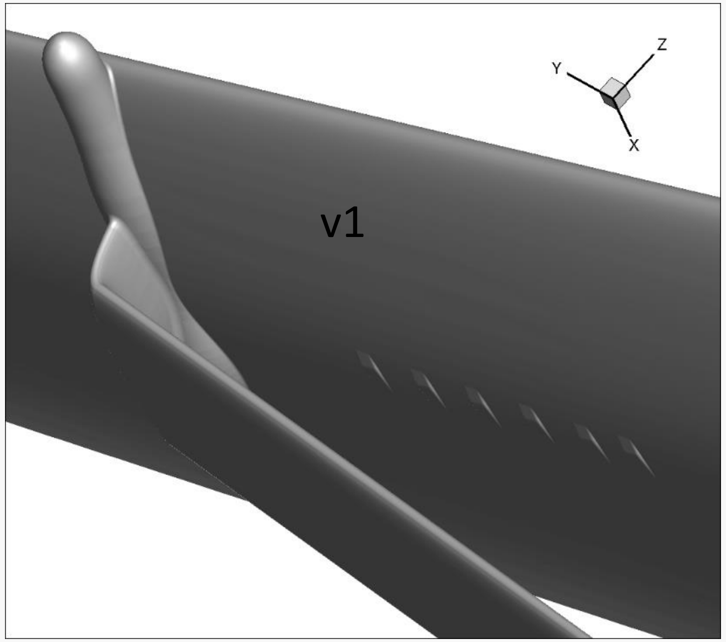
# Introduction

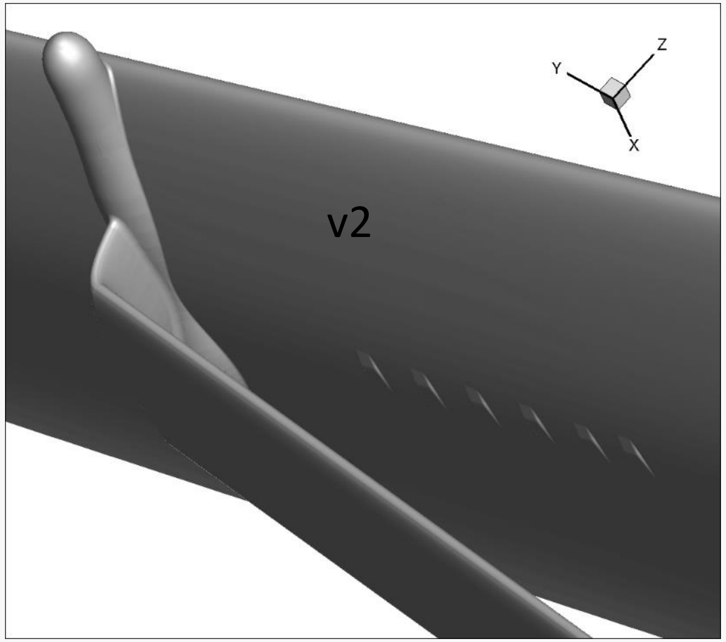
**Kuchemann’s Carrot + Shock Control Bumps**:

- Local effect of the KC + distributed effect of the SCB
- KC shape taken from previous model
- SCB shape taken from previous model
- SCBs repositioned (according to the shock position) and reduced in number due to massive flow detachment at y= 16m.



# Mesh & Solver

Solver - Ansys Fluent v18.0:

- density based solver
- Roe Scheme
- second order upwind with Barth – Jespersen slope limiter (1989)
- Modified 3 equation version of the **k-ω SST** turbulence model with several enhancements:
    - ✓ **Curvature correction** for the modeling of turbulence production (Smirnov & Menter, 2008)
    - ✓ **Compressibility effects** for the modeling of turbulence dissipation (Sarkar & Balakrishnan, 1990)
    - ✓ **Production Limiter** to limit the excessive generation of turbulence energy at stagnation points (Menter, 1994 + Kato & Launder, 1993) – standard practice for transition models
    - ✓ (the 3$^{rd}$ equation is for the) **Intermittency transition model** (Menter & Langtry, 2004) with **crossflow instability** (Arnal, 1984) to avoid Wilcox's - Low-Reynolds correction

Mesher – Numeca Hexpress

- Unstructured roughly 95M cells each configuration for the semi-span model.
- Full-hexahedral / cut-cell type
- Inflation layer: Y+ < 1 and growth rate = 1.15
- 6 cells on the trailing edge
- Refinement region in the wing-strut region from y=14.5m to y=17m
- Good control of mesh sizing from one geometry to another

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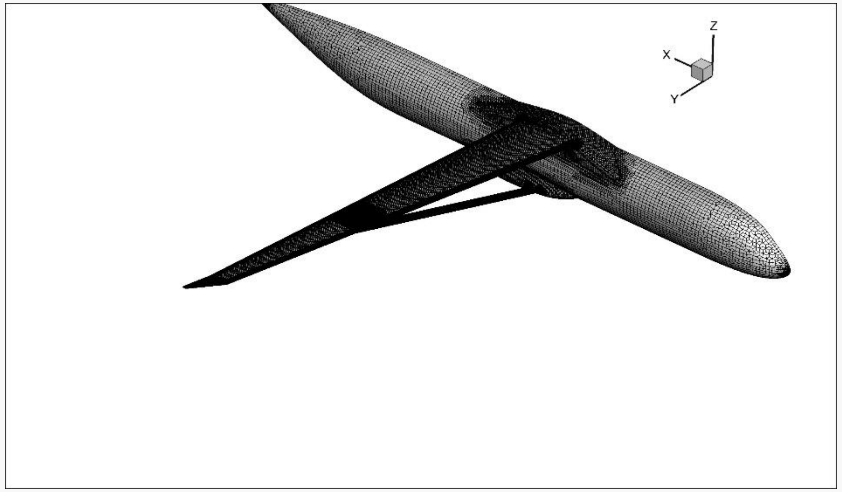
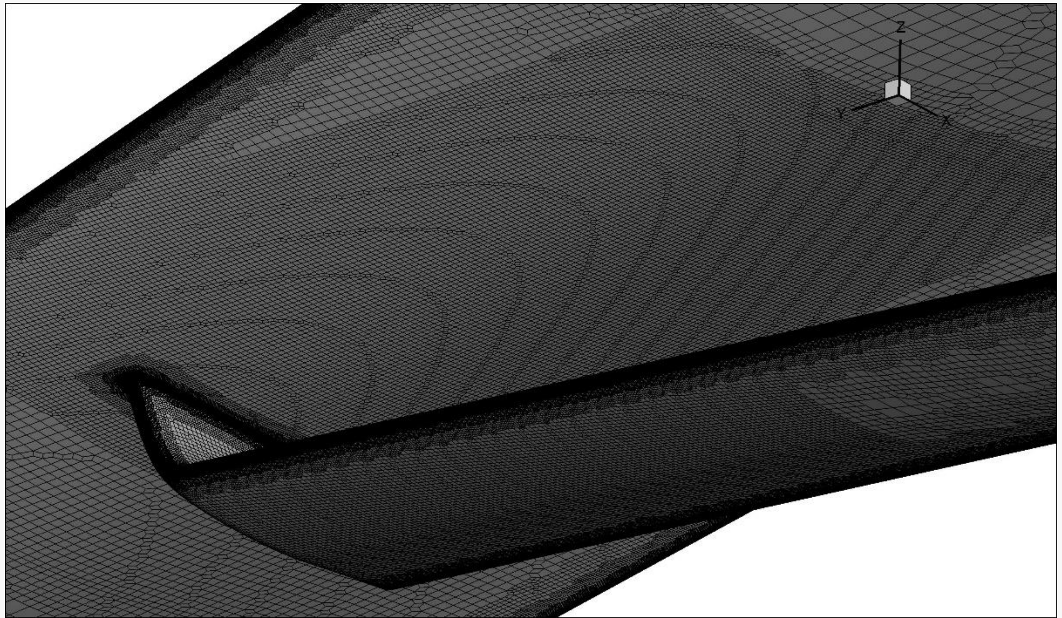
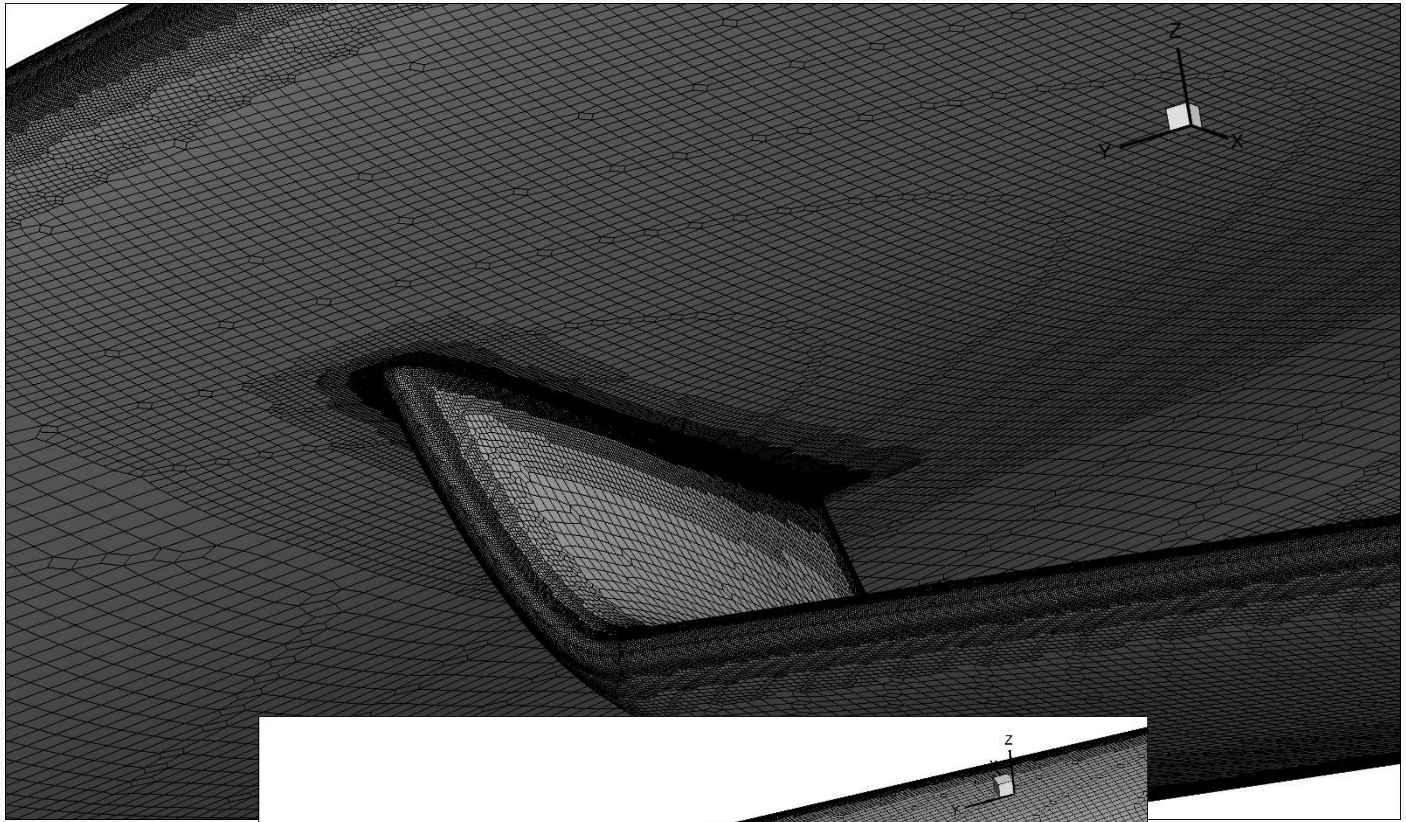
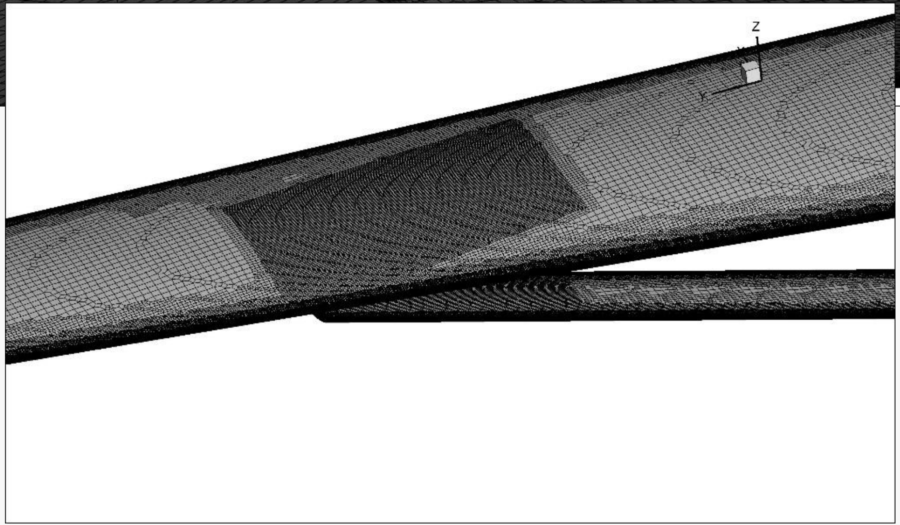
# Mesh & Solver

Base



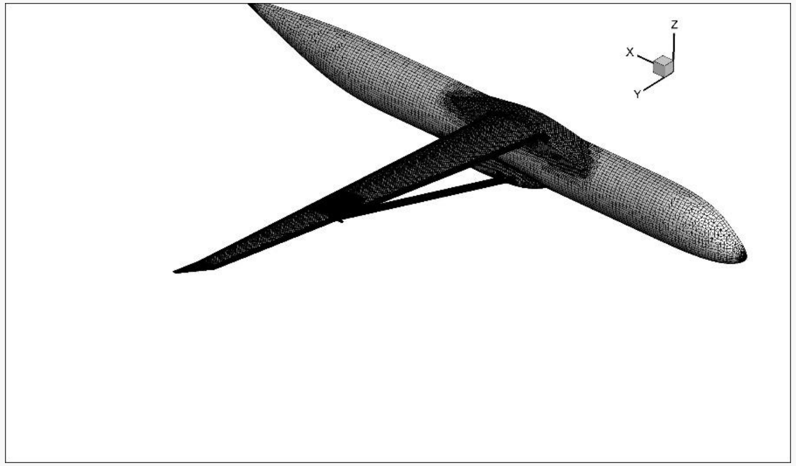


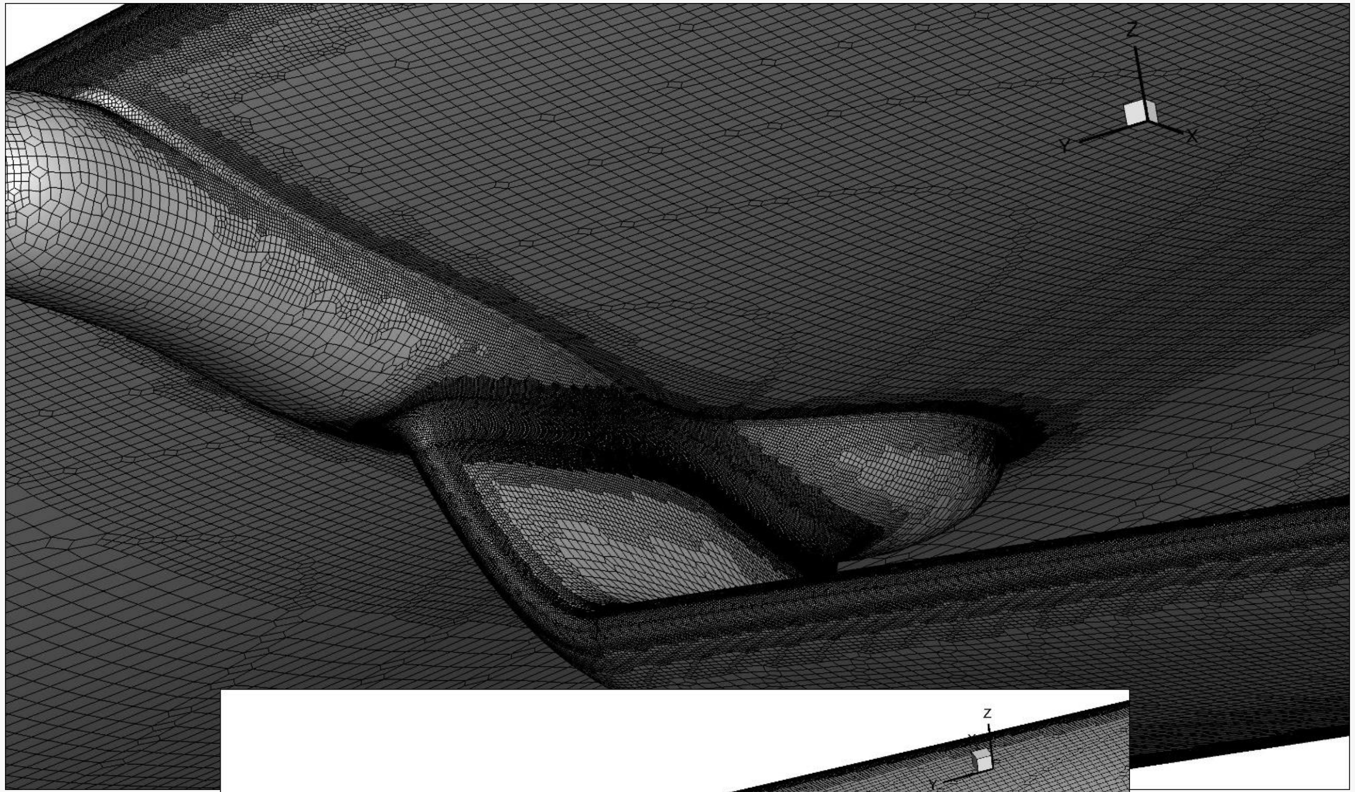


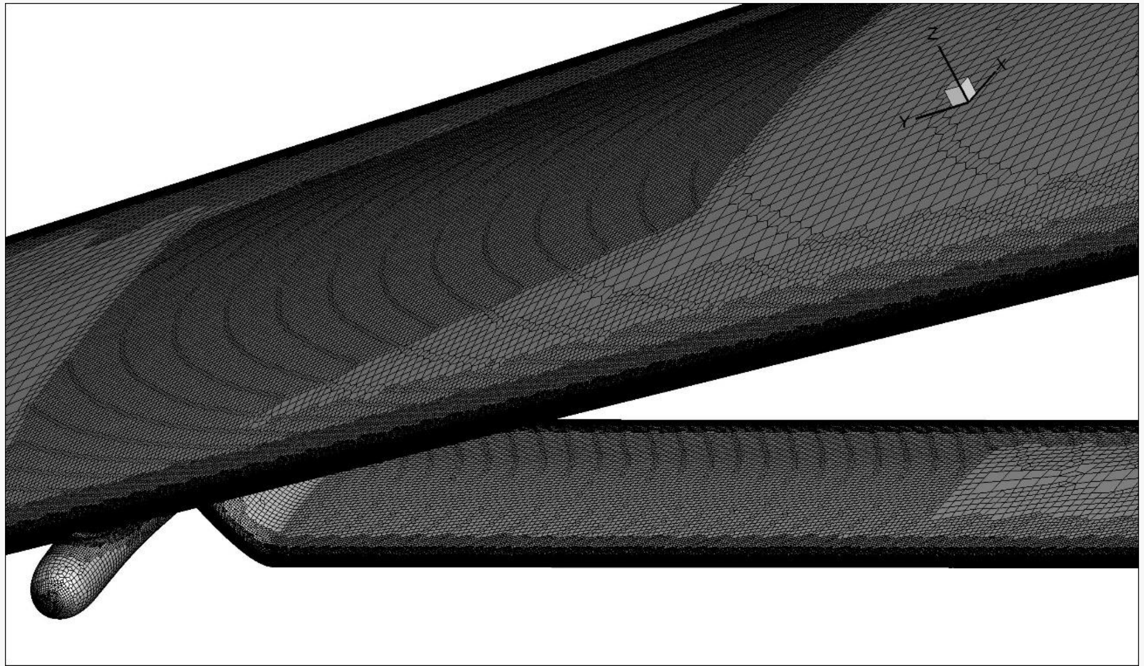


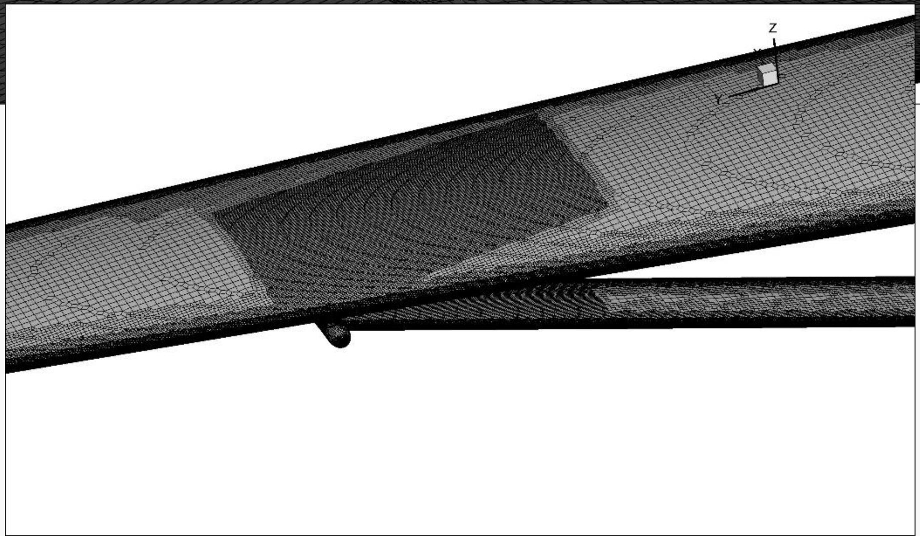
# Mesh & Solver

KC



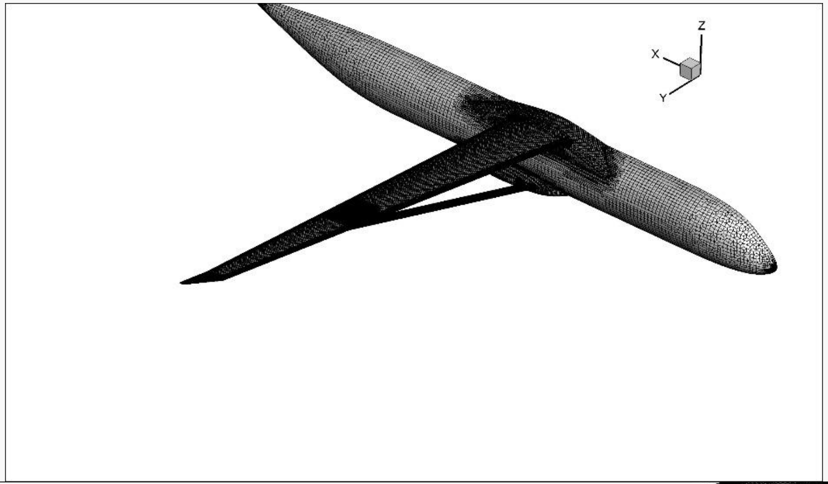


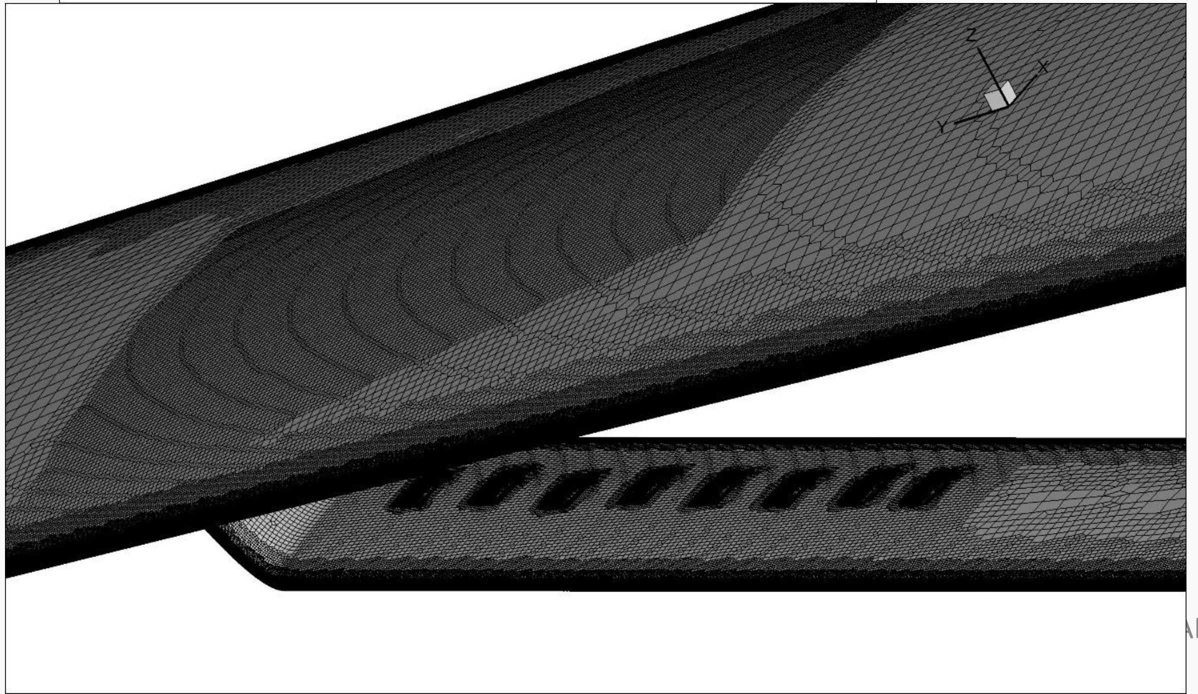


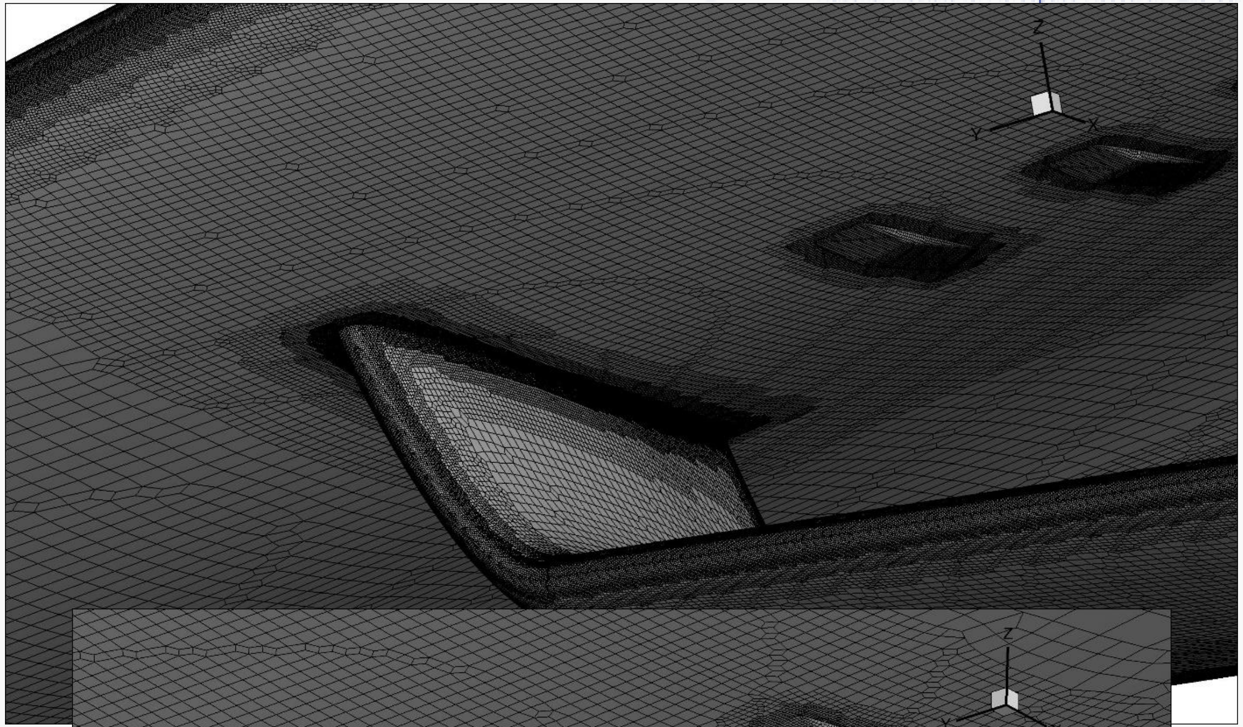


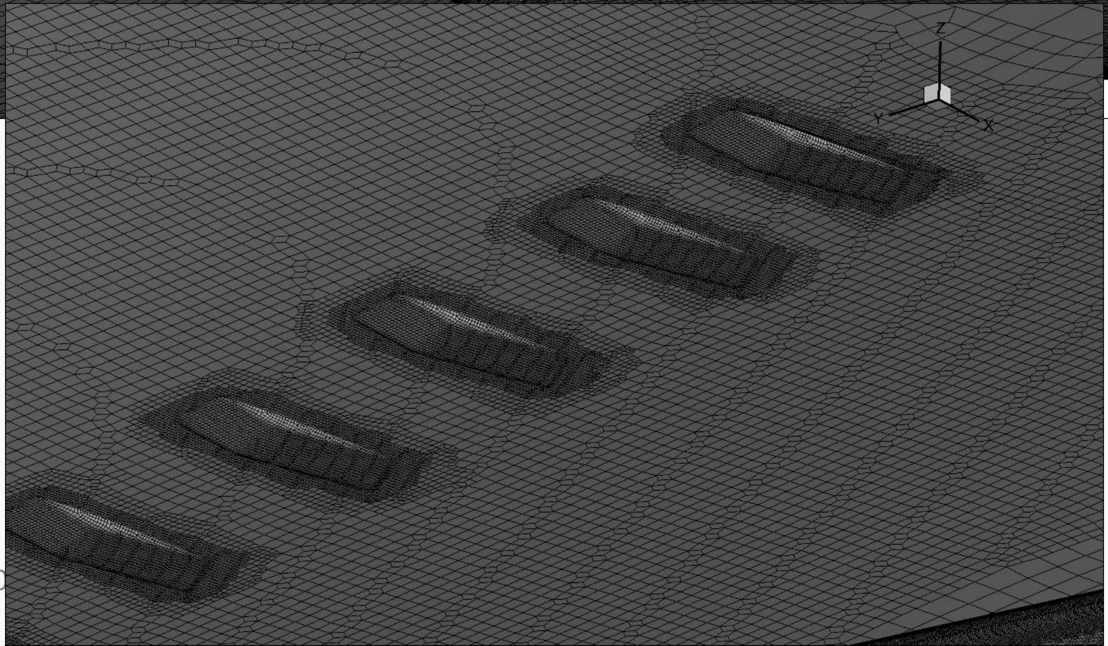
# Mesh & Solver

SCB









# Results

The flow conditions are summarized as:

- Mach 0.72, angle of attack 1$^o$
- Cruise altitude 30000ft on an atmosphere ISA+0 with:
  - pressure 30089.59 Pa,
  - temperature 228.71K.
- The reference area is S = 80.5 m$^2$,semi-span model
- The reference length is 3.264m.

| Configuration | Lift | Drag | L/D | aoa |
|---|---|---|---|---|
| **Base** | **0.383** | **0.02281** | **16.77208** | **1** |
| KC | 0.385 | 0.02278 | 16.91656 | 1 |
| SCB | 0.379 | 0.02269 | 16.69289 | 1 |
| **KC_Lift_match** | **0.383** | **0.02274** | **16.83658** | **0.98** |
| **SCB_Lift_match** | **0.383** | **0.02275** | **16.84163** | **1.03** |
| kc_scb_v0 | 0.386 | 0.02310 | 16.72154 | 1 |
| kc_scb_v1 | 0.383 | 0.02296 | 16.68633 | 1 |
| kc_scb_v2 | 0.383 | 0.02289 | 16.72369 | 1 |

Drag breakdown:

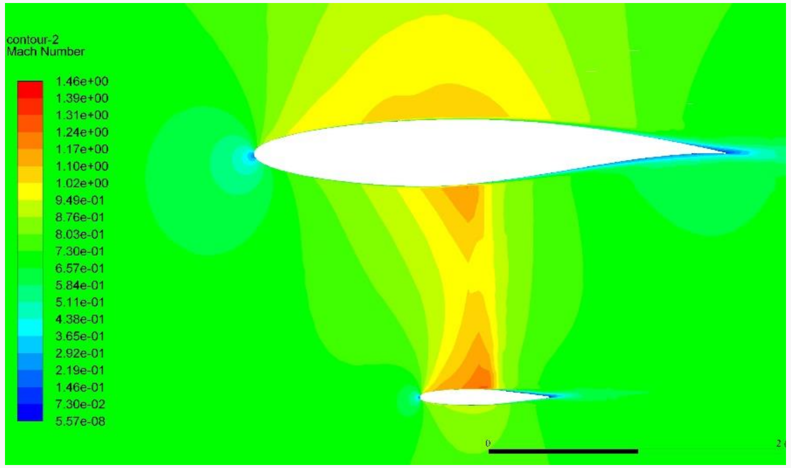
| Configuration | pressureDrag | viscousDrag | delta_visc | delta_pres |
|---|---|---|---|---|
| **Base** | **0.01173867** | **0.01107338** | -- | -- |
| KC | 0.011690303 | 0.01108774 | -1E-05 | 5E-05 |
| SCB | 0.011646659 | 0.01104708 | 3E-05 | 9E-05 |
| **KC_Lift_match** | **0.011652629** | **0.01108774** | **-1E-05** | **9E-05** |
| **SCB_Lift_match** | **0.011700992** | **0.01104617** | **3E-05** | **4E-05** |

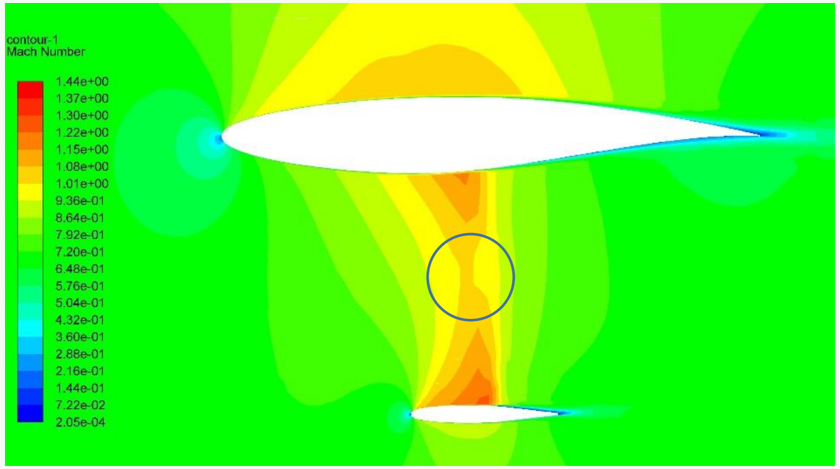
# Results

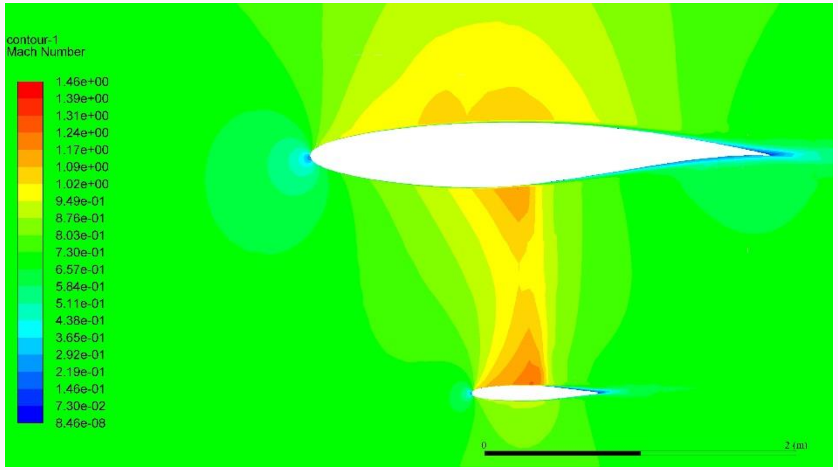
Baseline

Kuchemann Carrot

Shock Control Bump

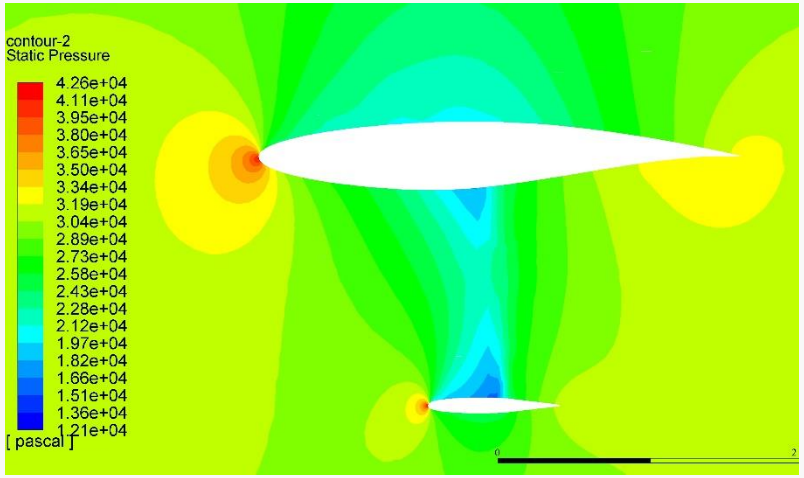


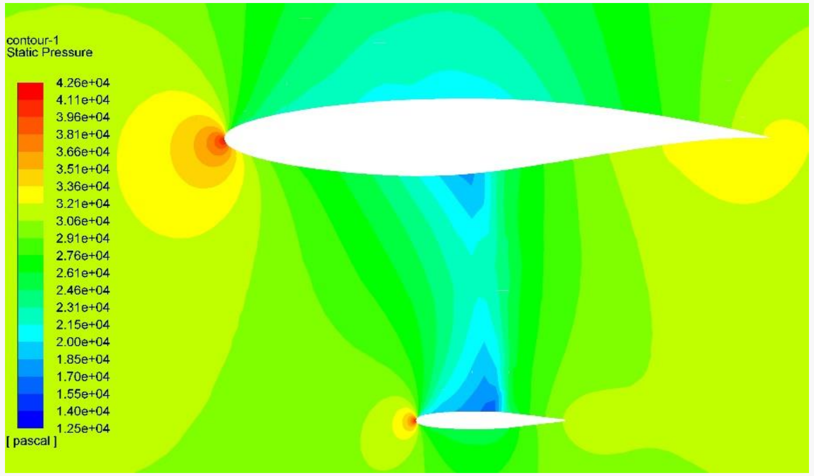



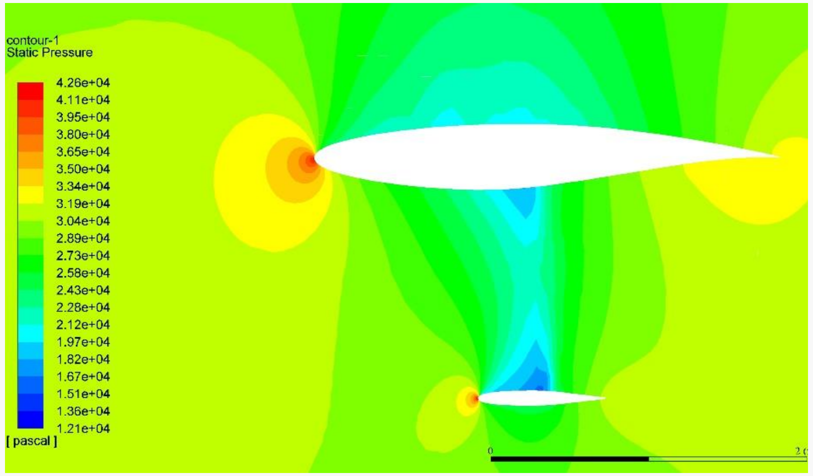




Y slice =12m

Little / No difference



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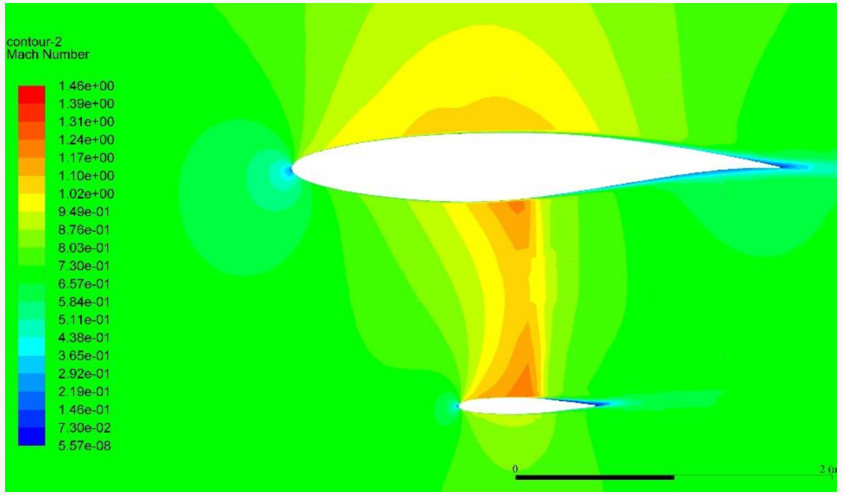
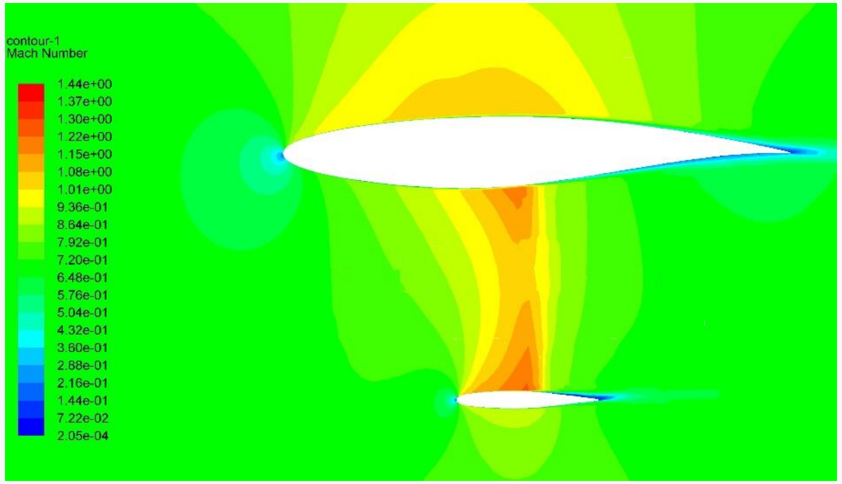
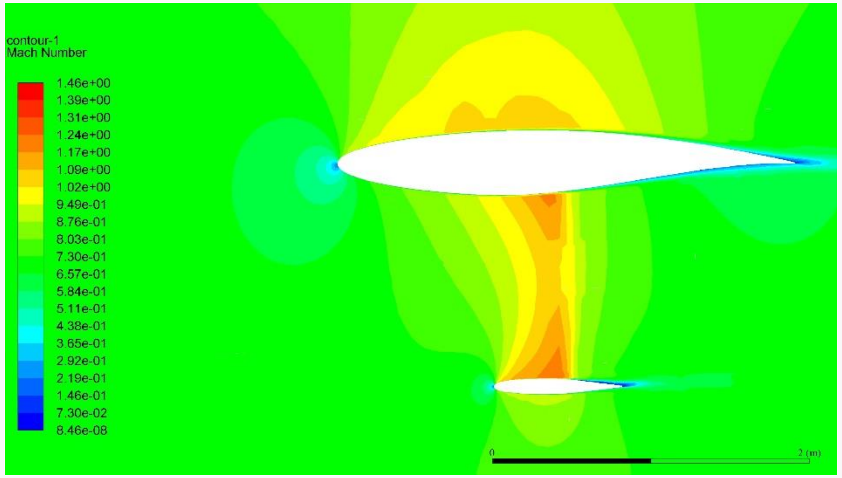
# Results

| Baseline | Kuchemann Carrot | Shock Control Bump |
|---|---|---|

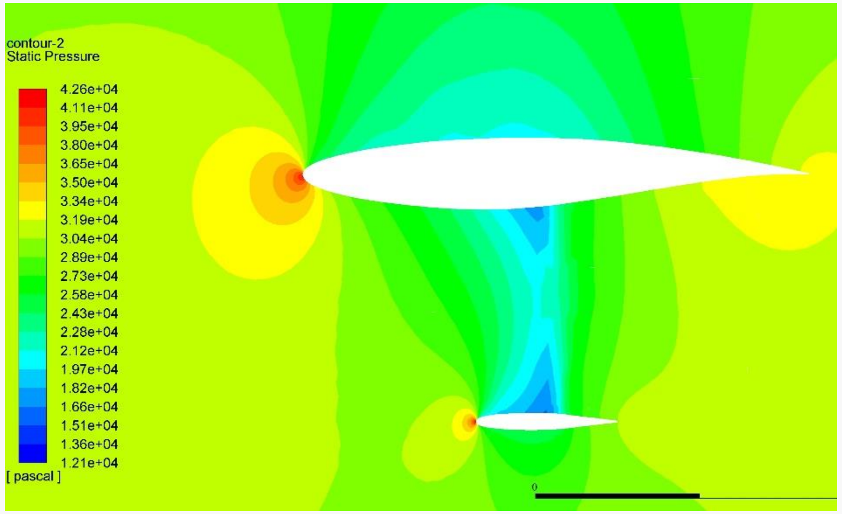


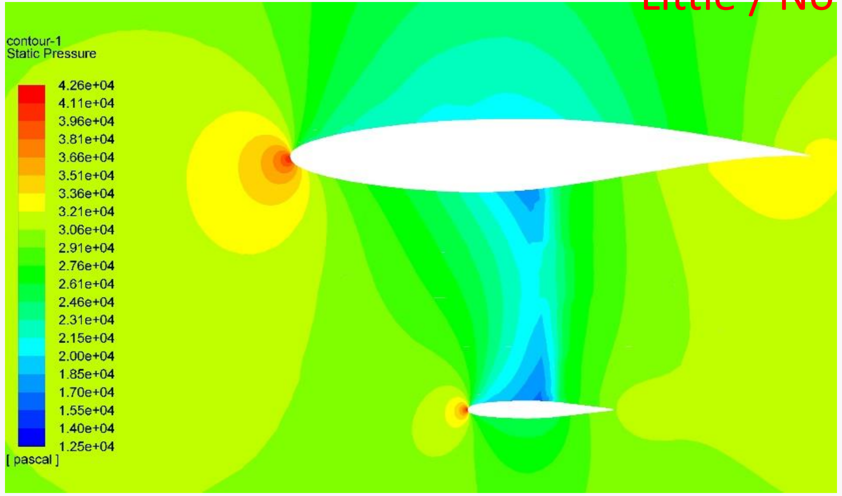



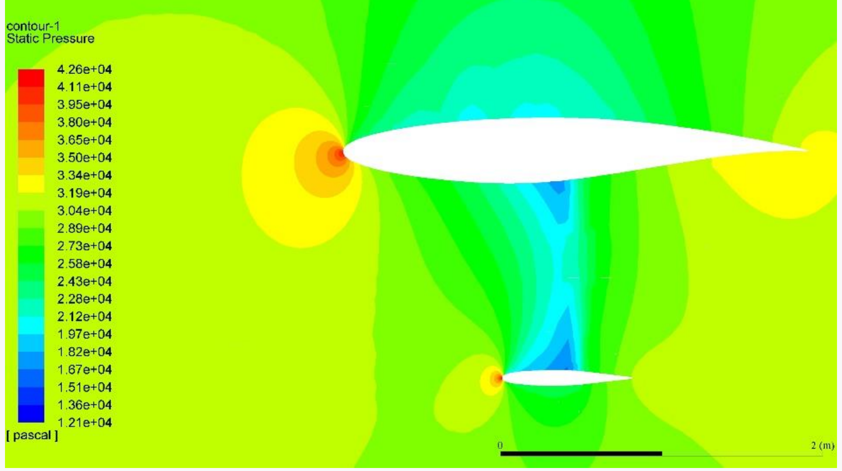




Y slice =12.5m

Little / No difference



# Results

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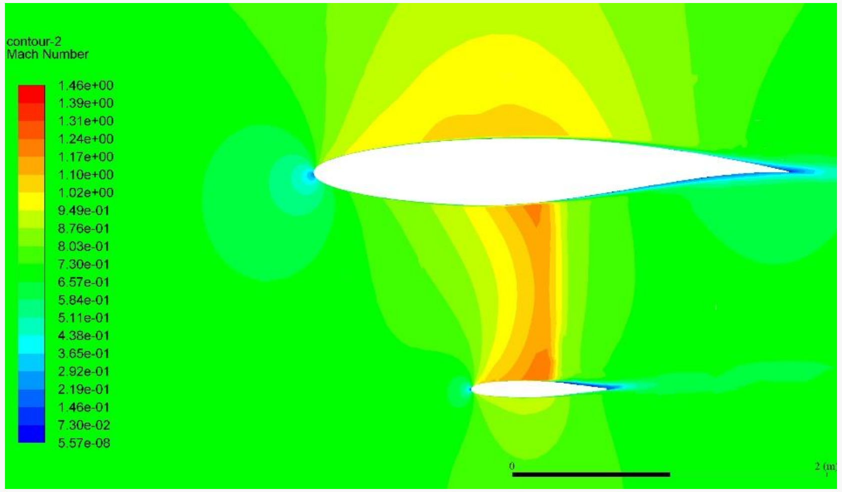
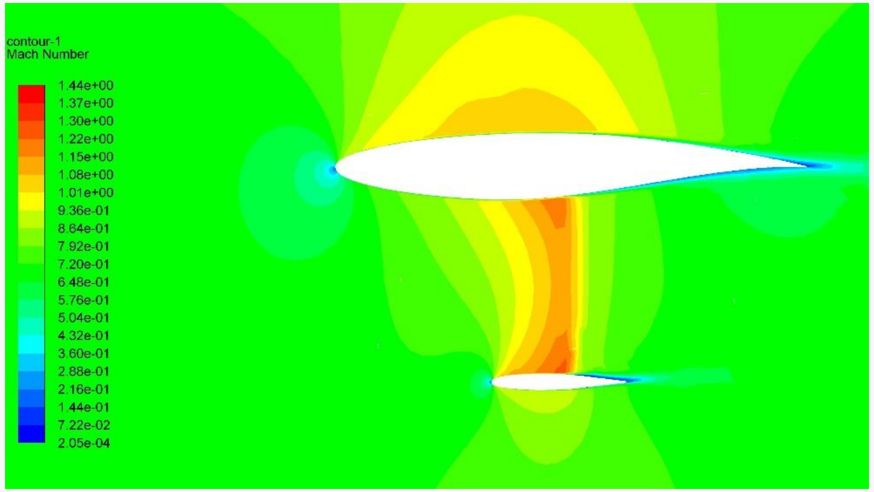
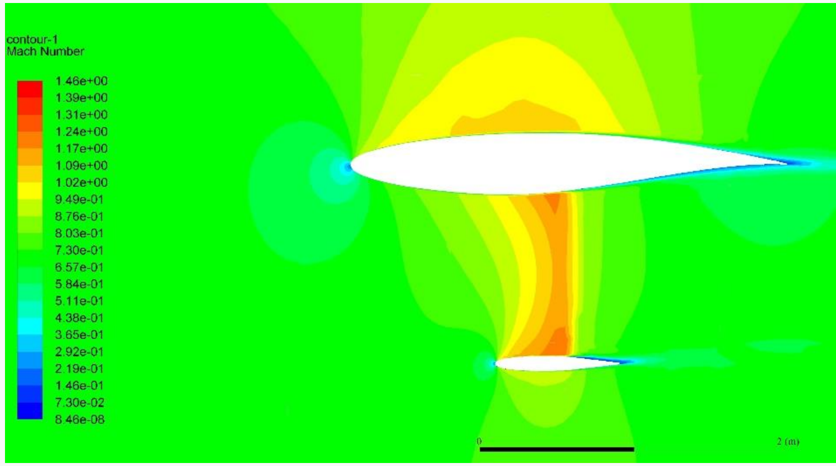
Baseline | Kuchemann Carrot | Shock Control Bump

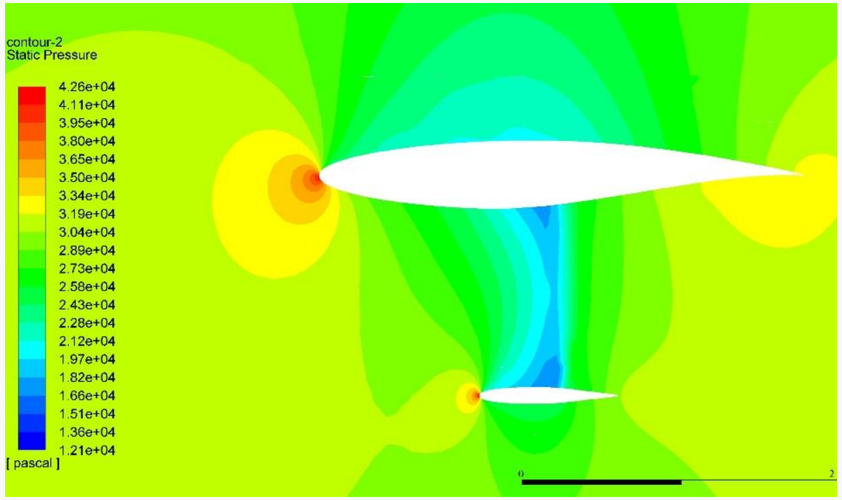


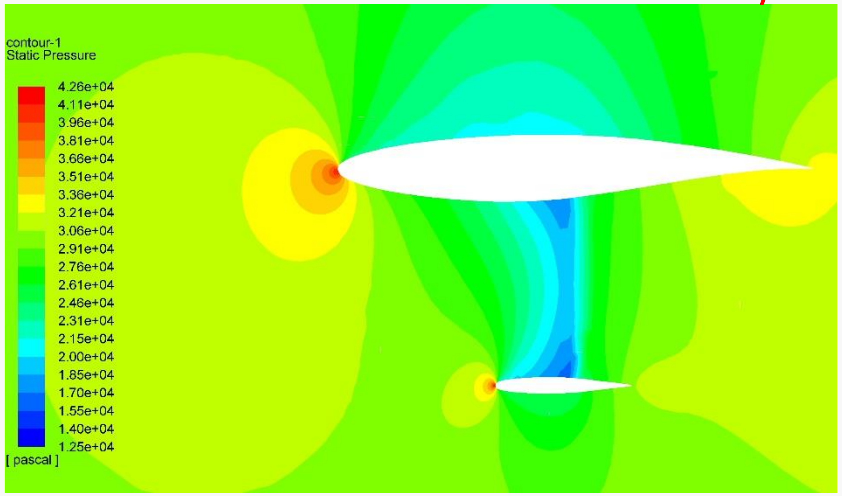



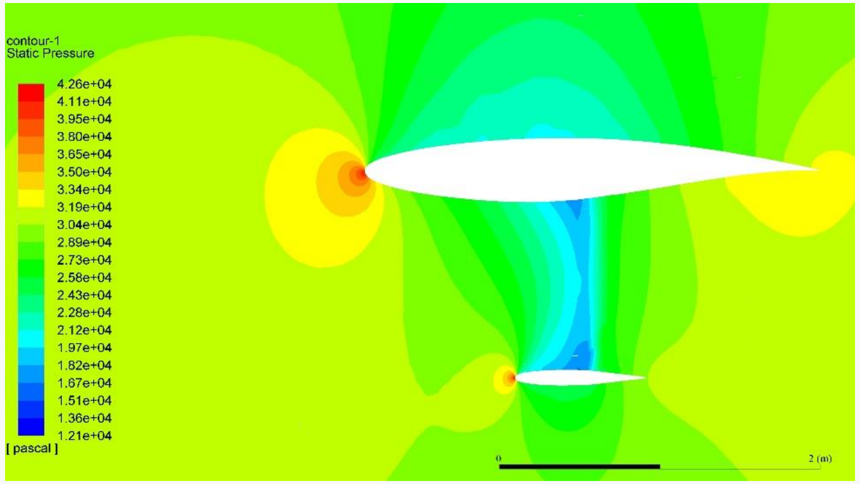




Y slice =13m

Little / No difference



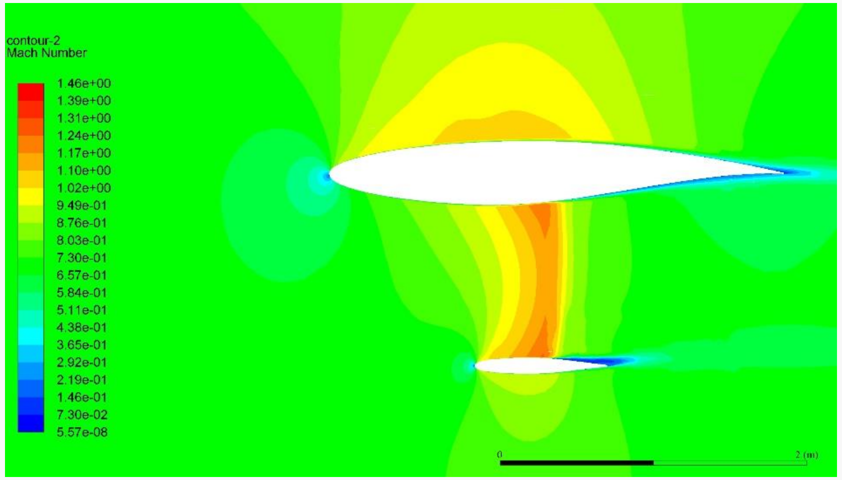



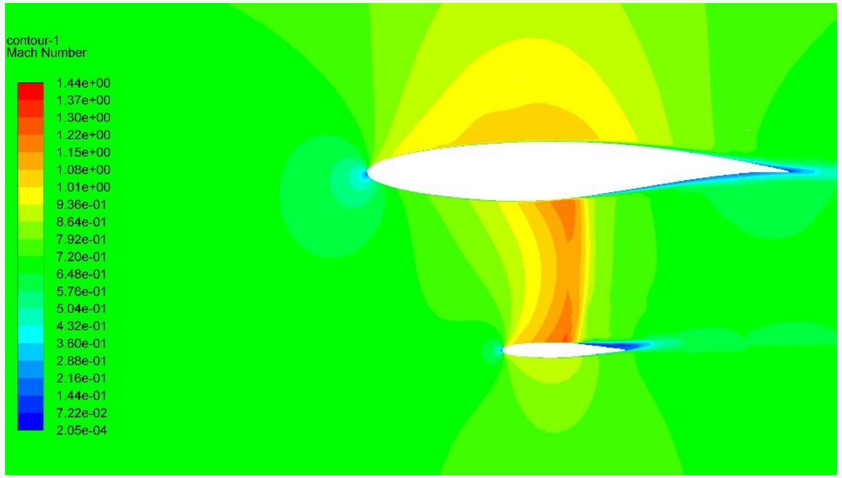



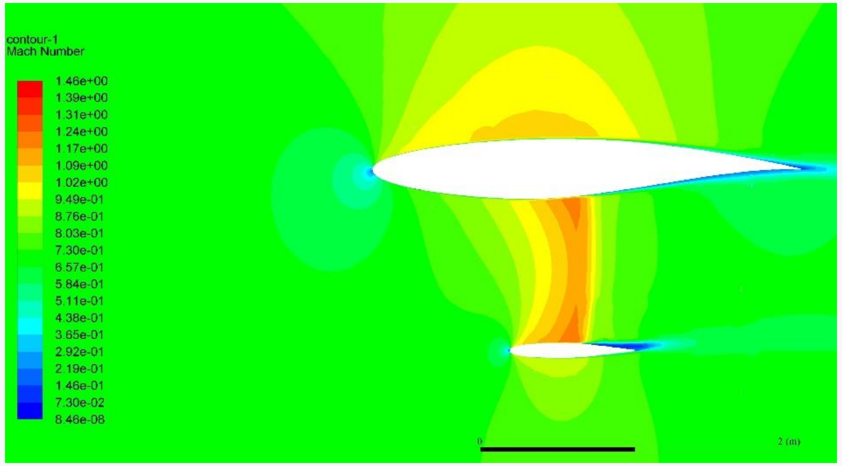
# Results

National Institute for Aerospace Research "Elie Carafoli"

Baseline | Kuchemann Carrot | Shock Control Bump

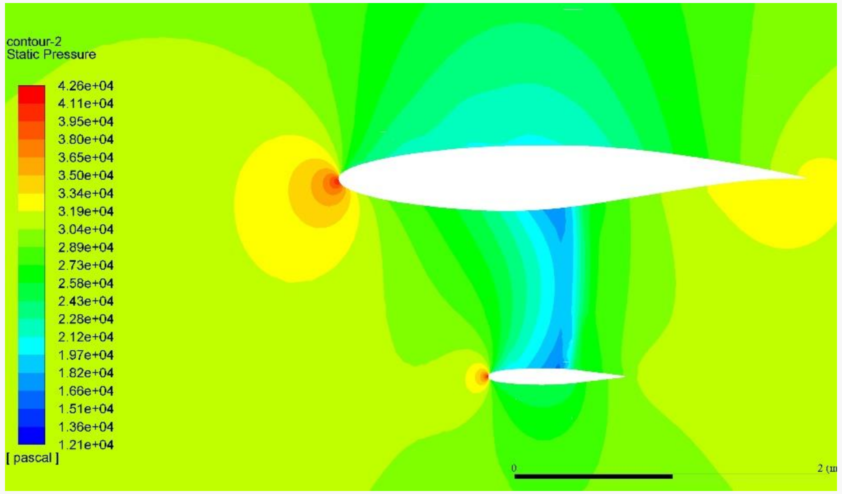


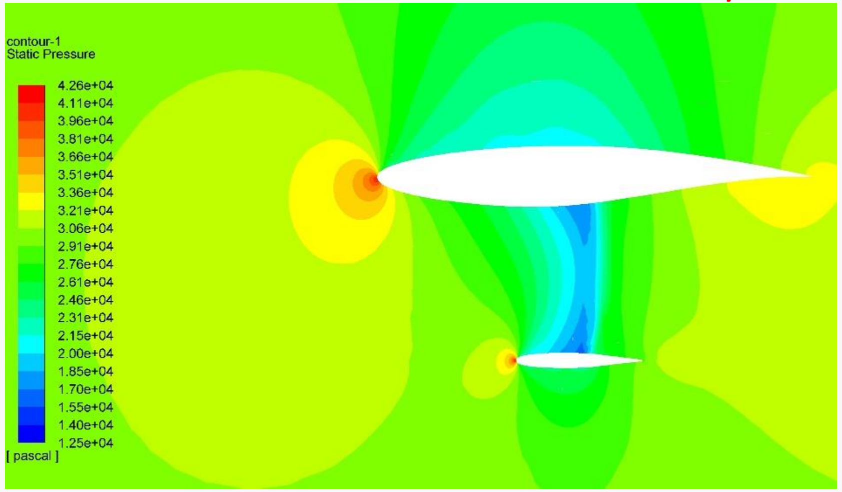



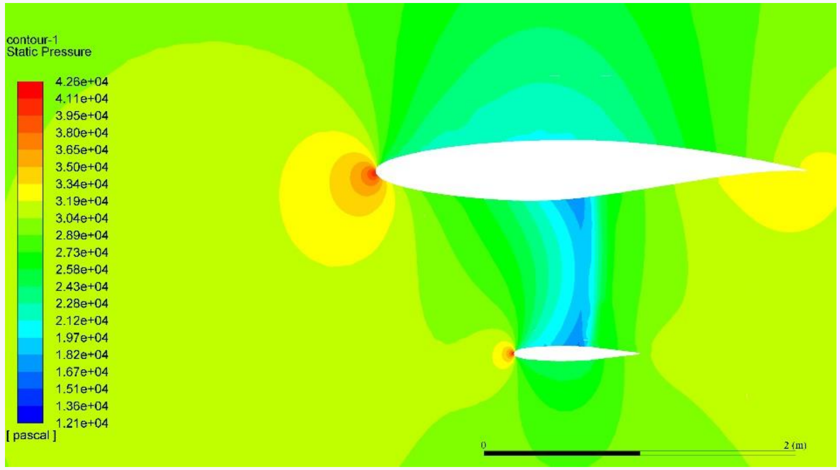




Y slice =13.5m

Little / No difference



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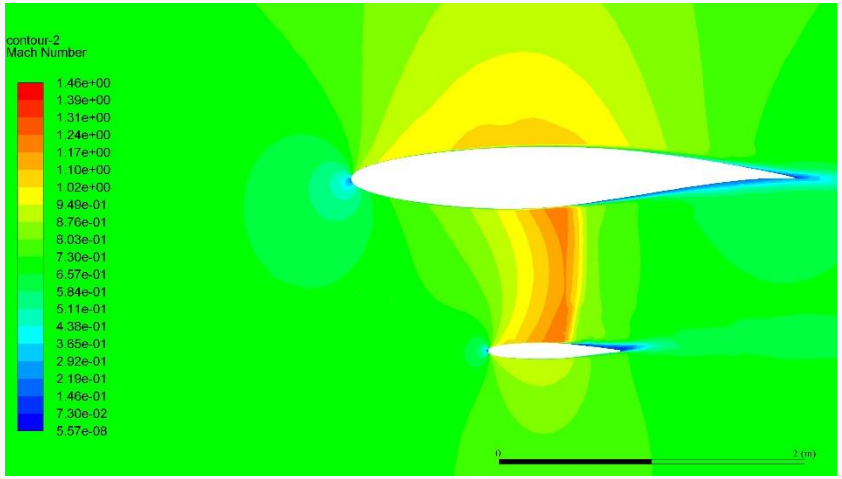
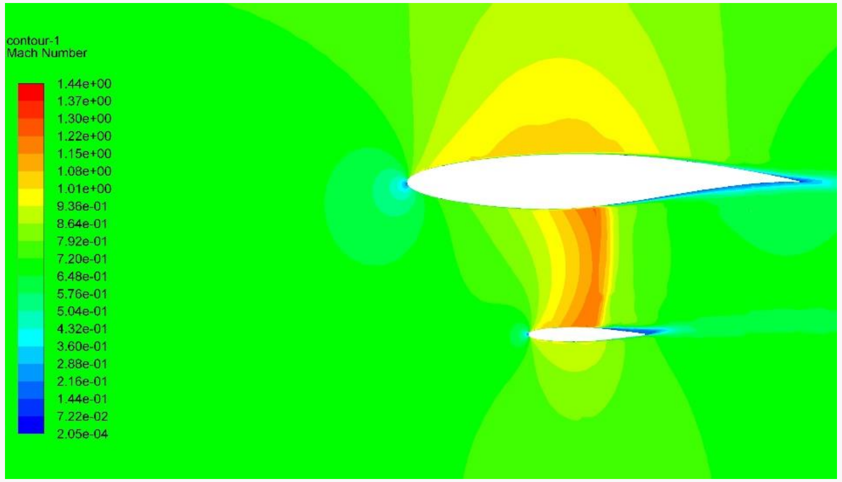
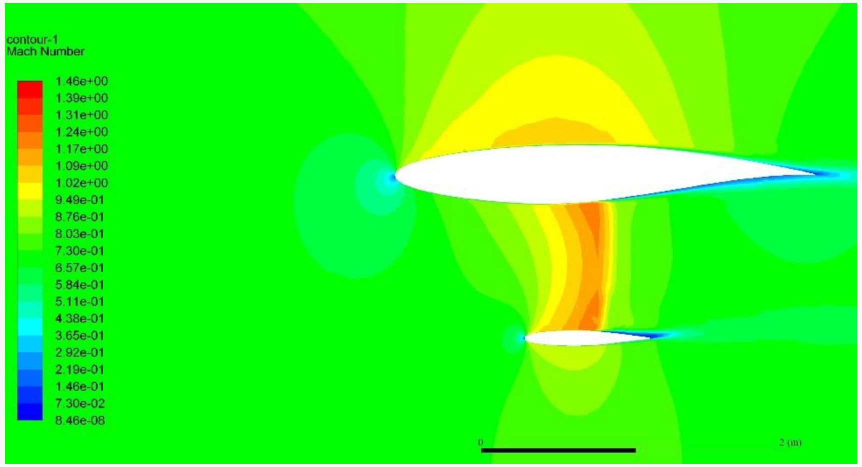
| Baseline | Kuchemann Carrot | Shock Control Bump |
|---|---|---|

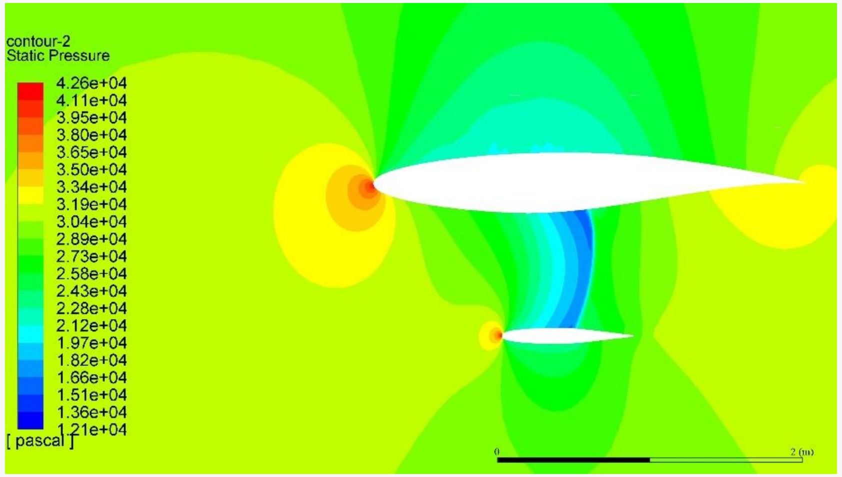


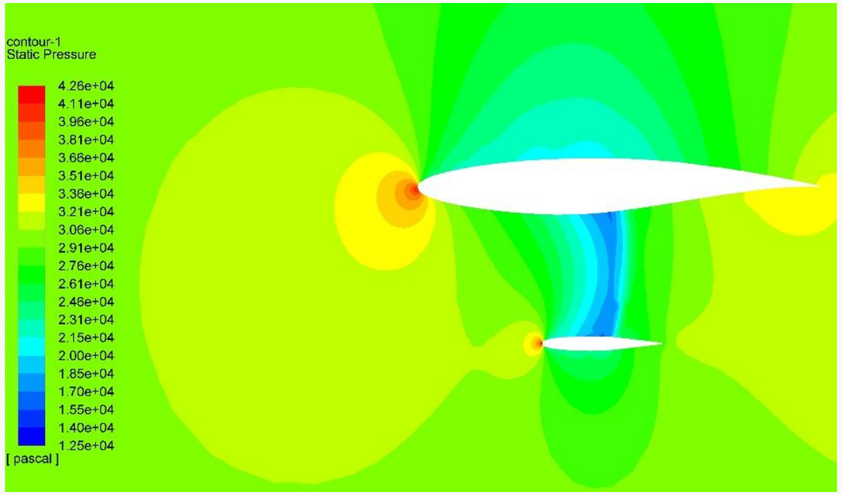



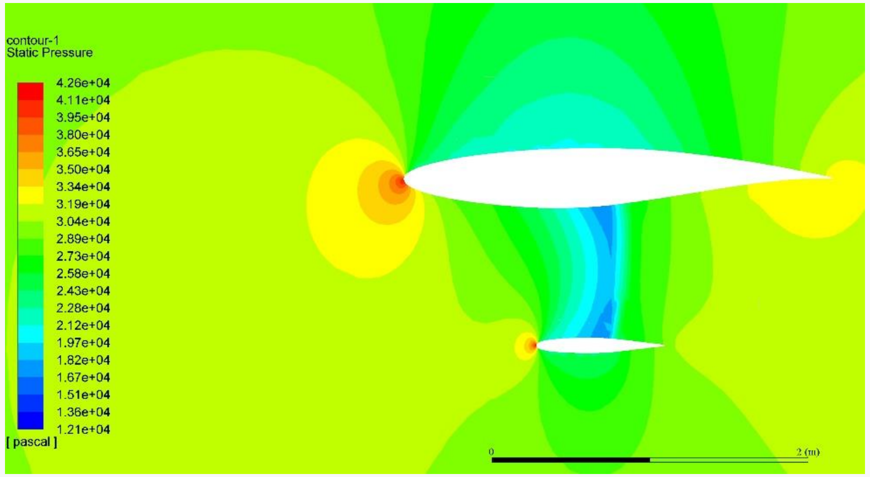




Y slice =14m

Little / No difference



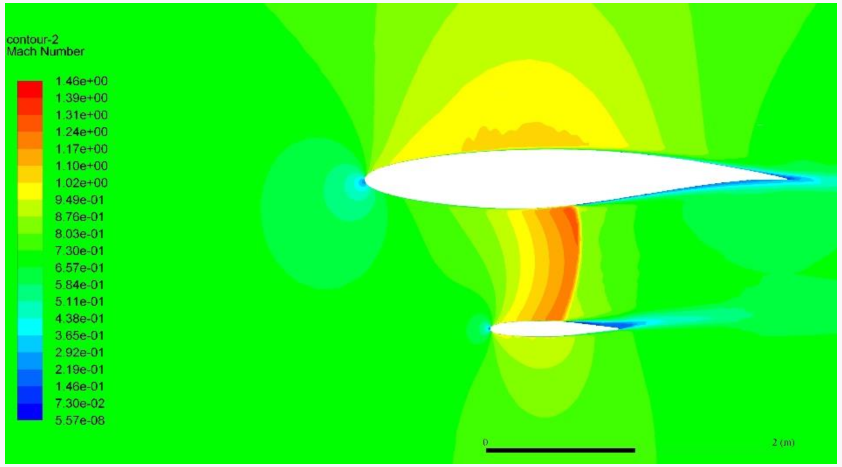



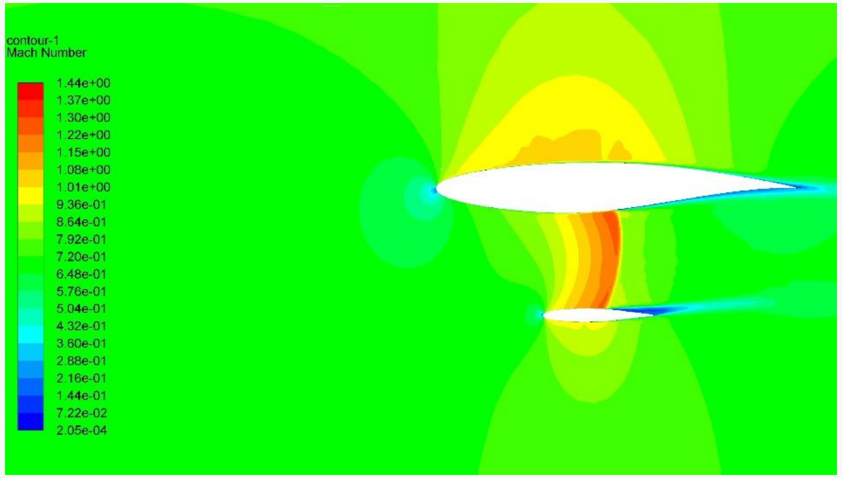



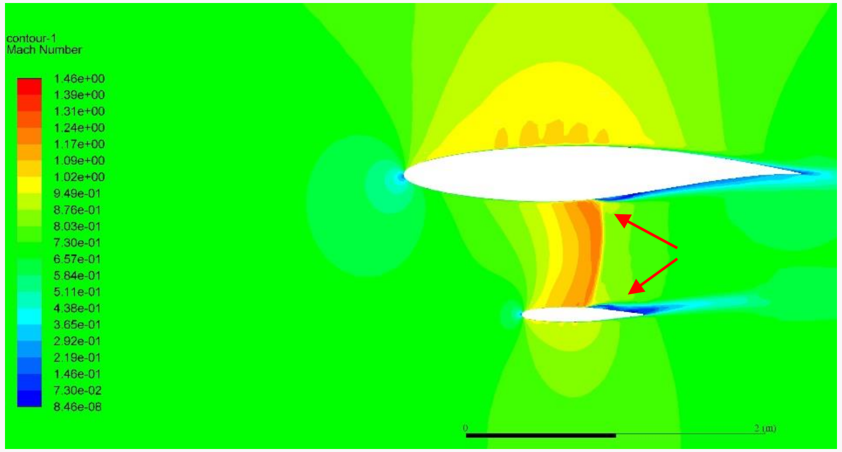
# Results

National Institute for Aerospace Research "Elie Carafoli"

Baseline | Kuchemann Carrot | Shock Control Bump

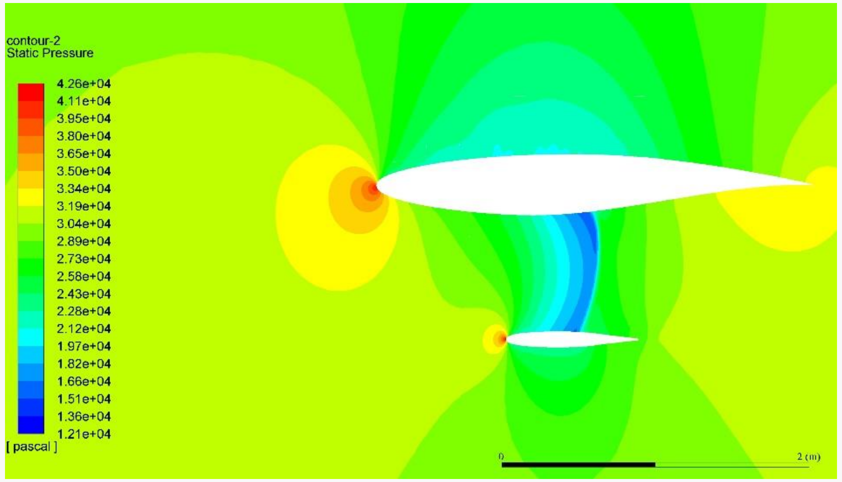


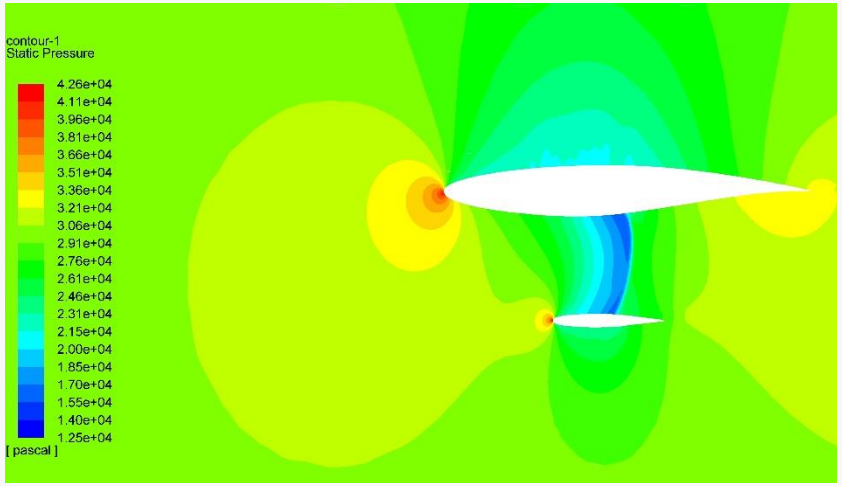



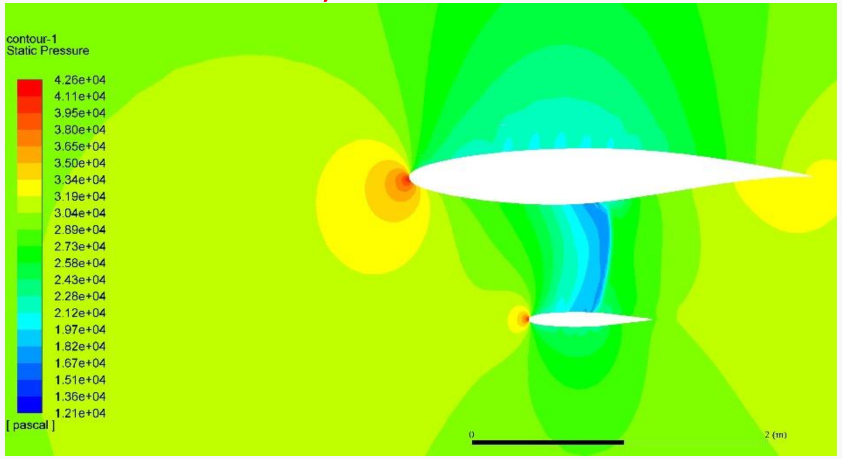




Y slice =14.5m

Little / No difference for KC; detached flow SCB

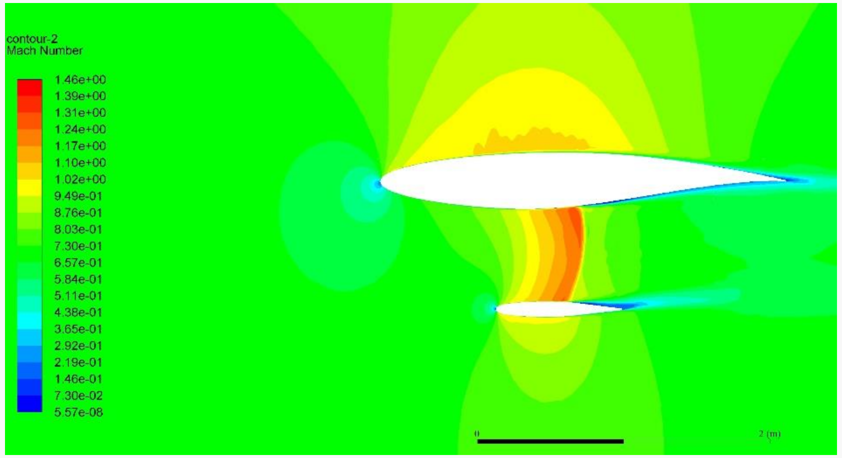


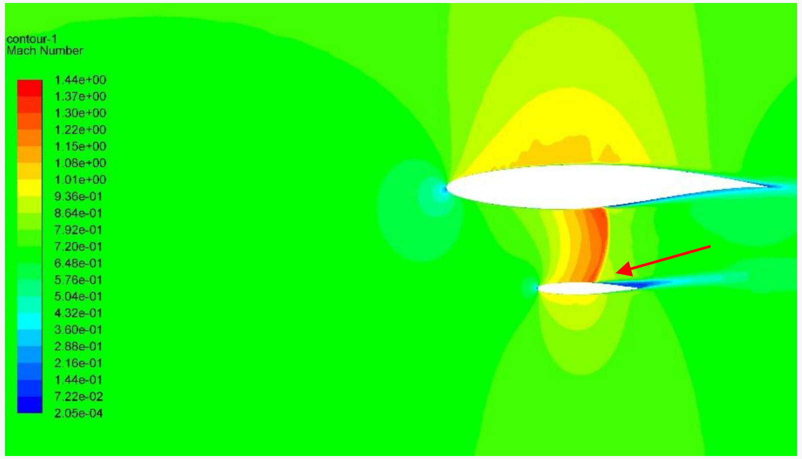



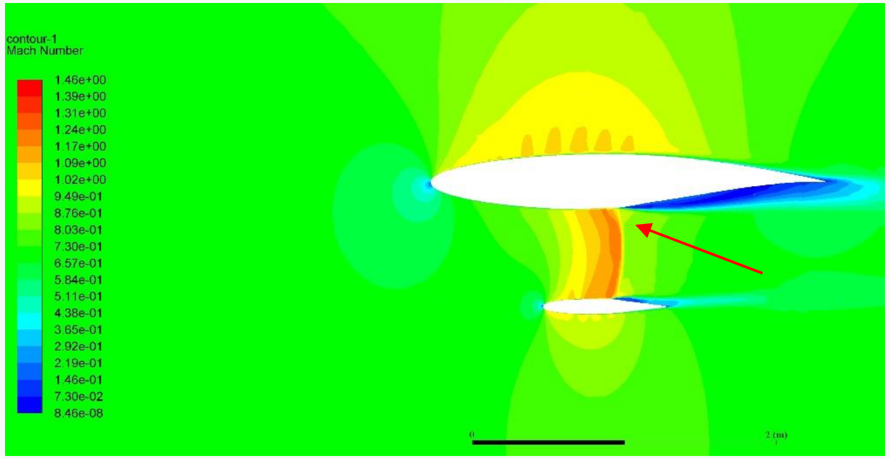



# Results

Baseline | Kuchemann Carrot | Shock Control Bump

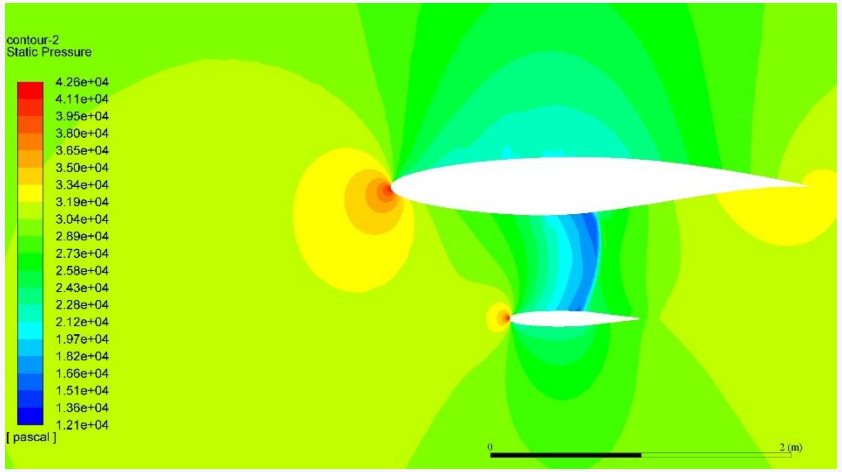


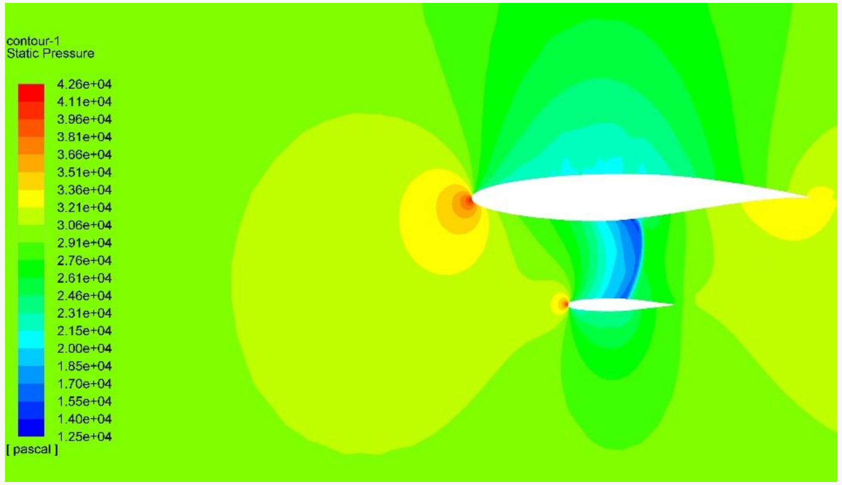



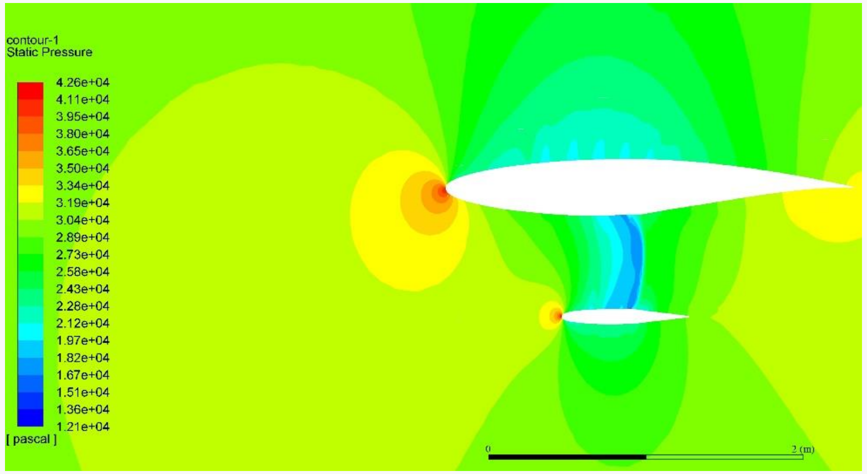




Y slice =15m

detached flow SCB and less on KC

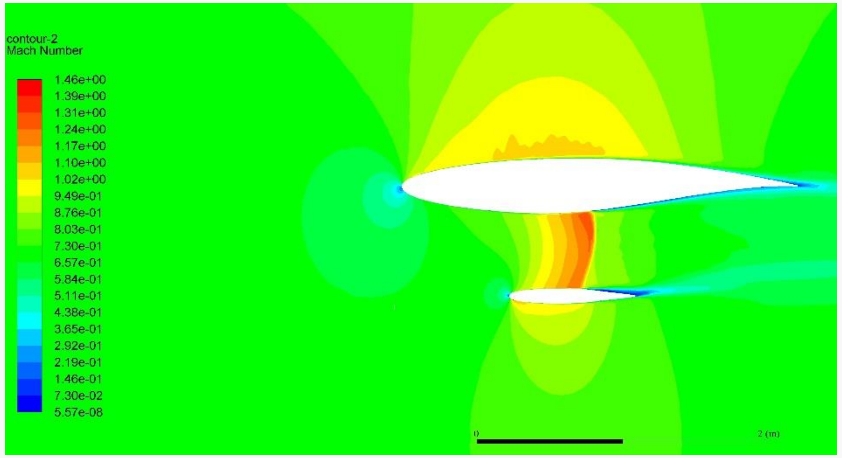


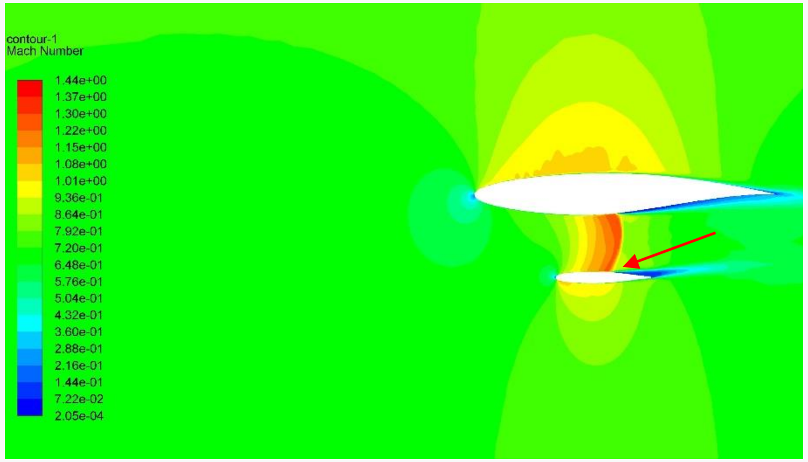



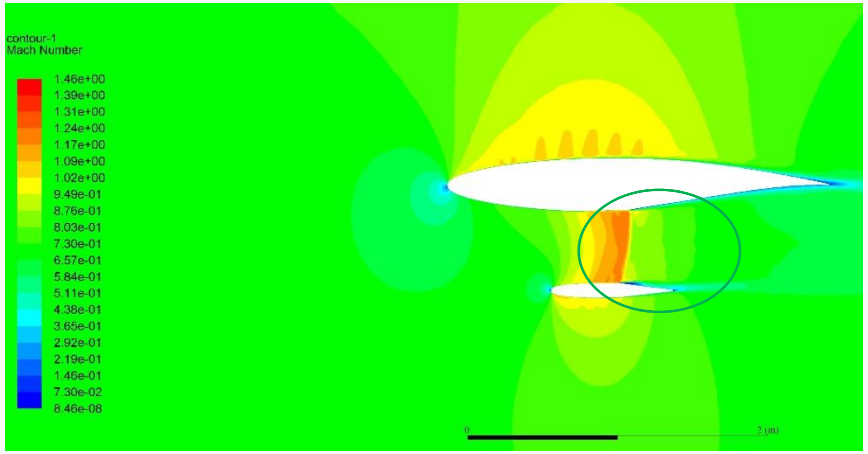



# Results

| Baseline | Kuchemann Carrot | Shock Control Bump |
|---|---|---|

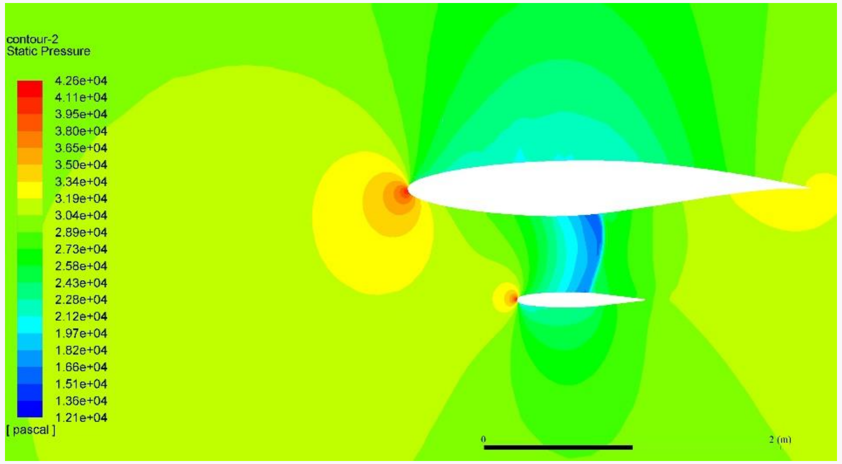


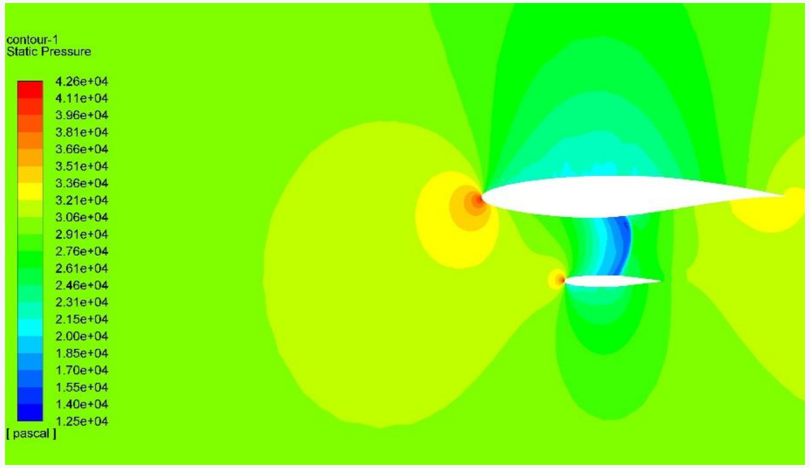



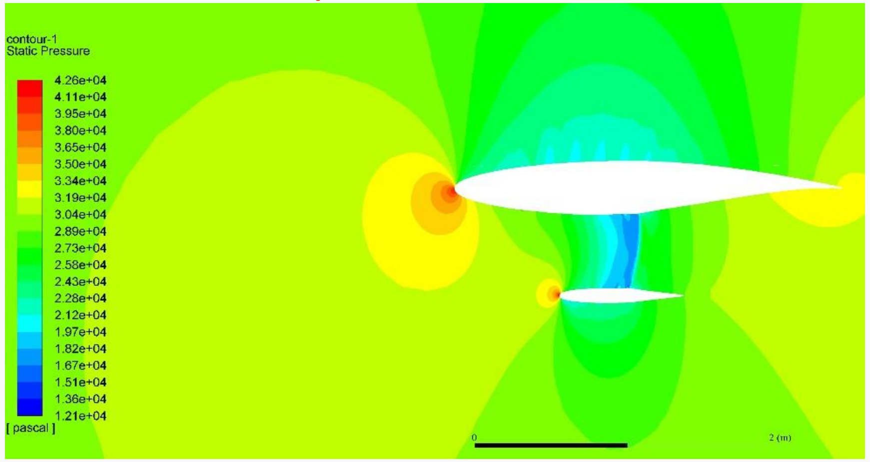




Y slice =15.5m

No detached flow SCB; separation for KC

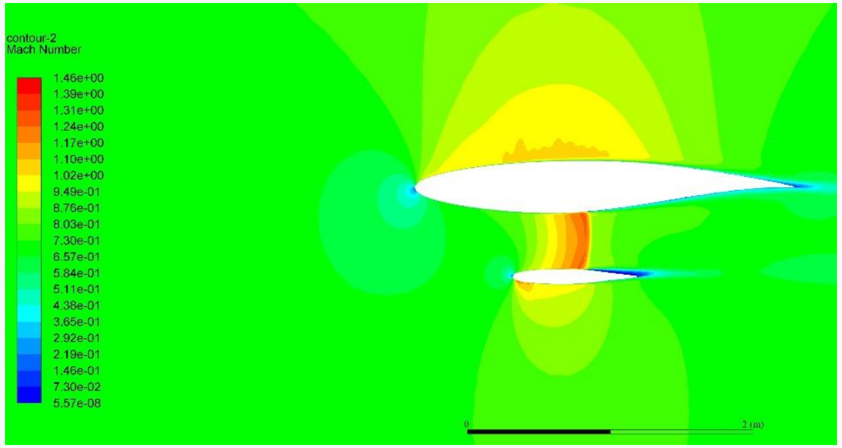


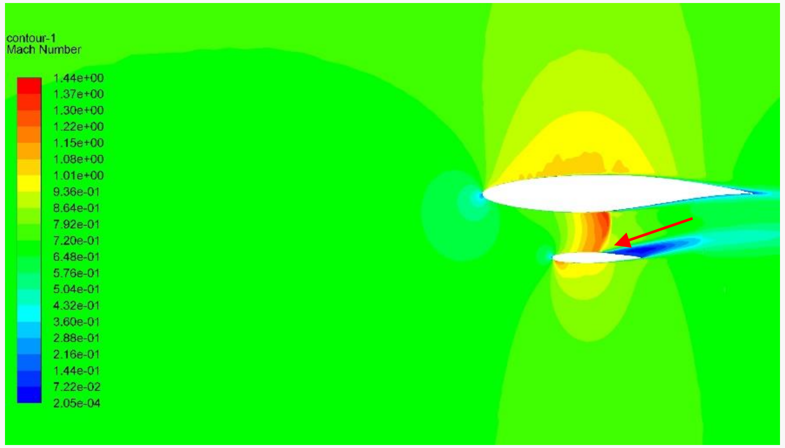



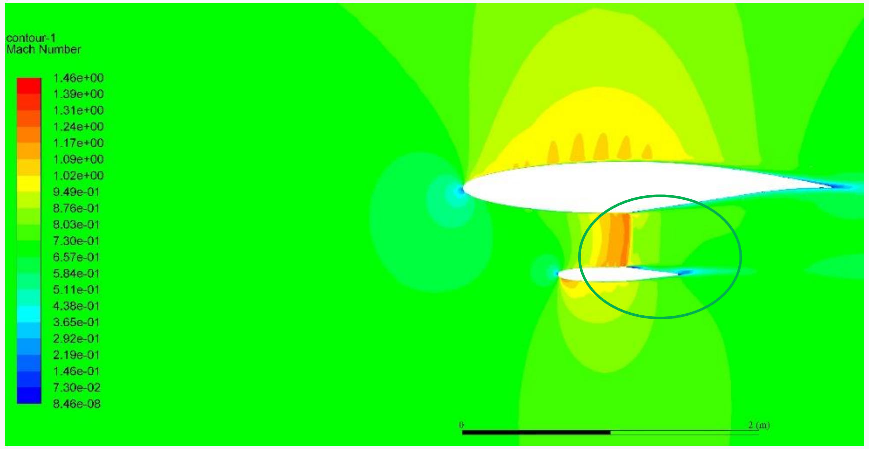



# Results

| Baseline | Kuchemann Carrot | Shock Control Bump |
|---|---|---|

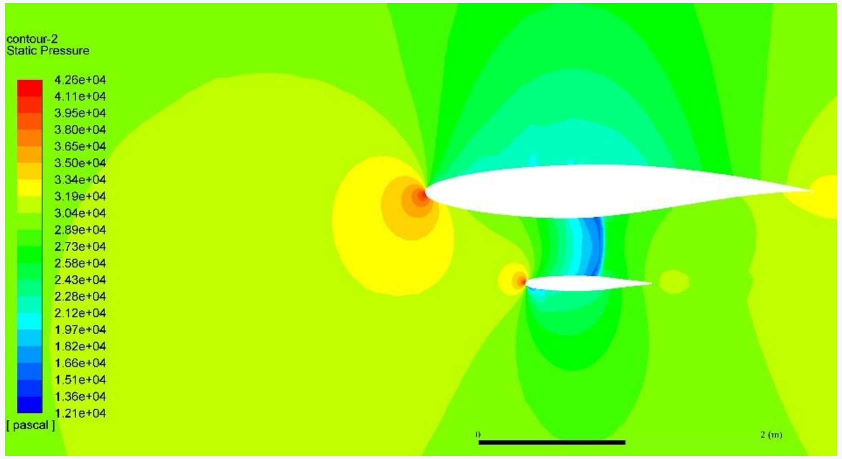


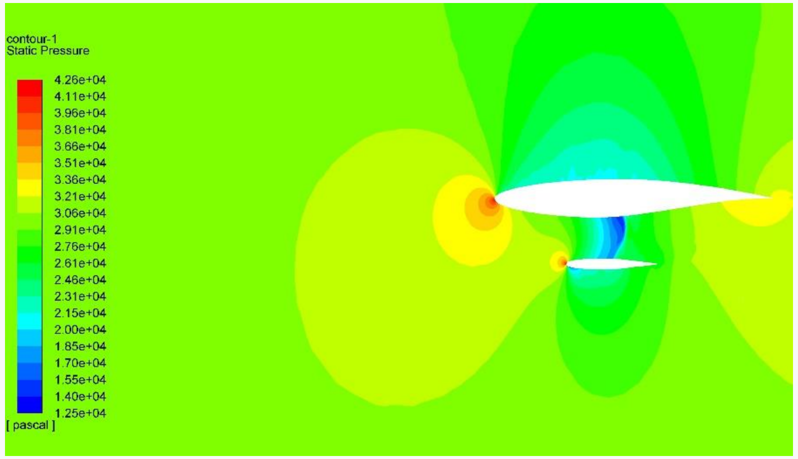



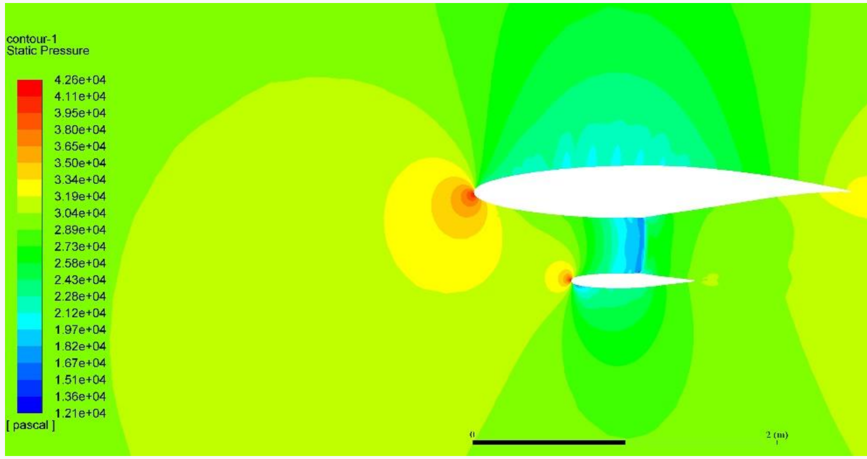




Y slice =16m

No detached flow SCB; separation for KC



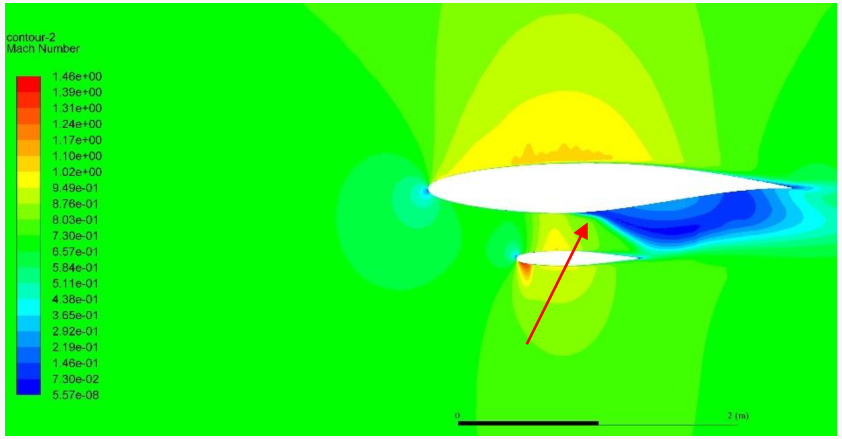



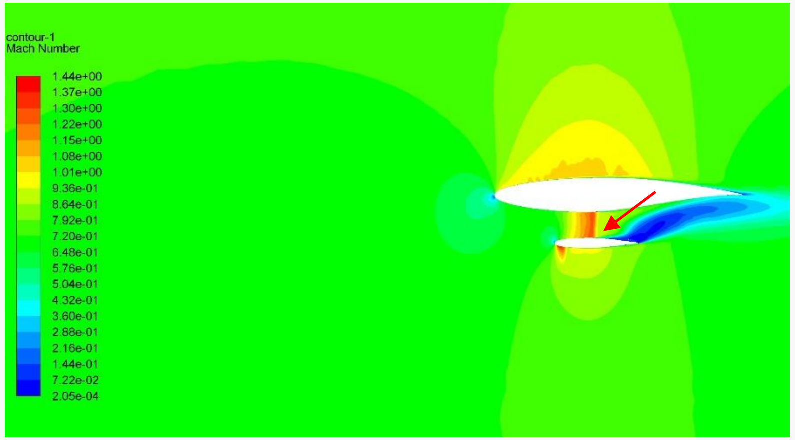



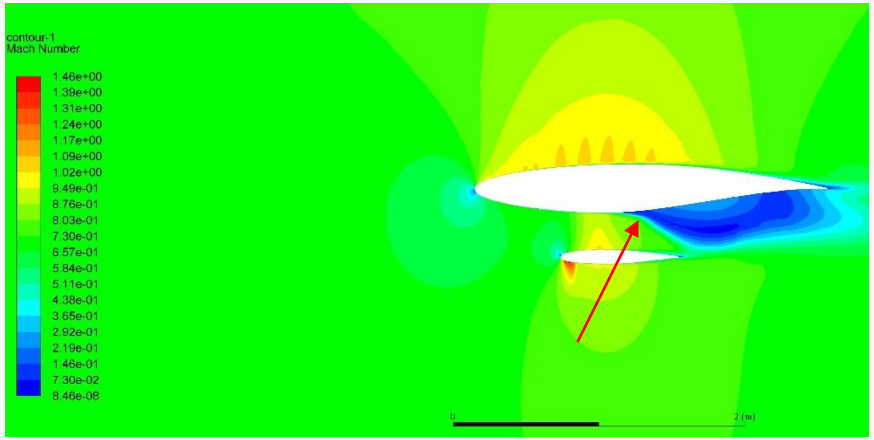
# Results

National Institute for Aerospace Research "Elie Carafoli"

| Baseline | Kuchemann Carrot | Shock Control Bump |
|---|---|---|

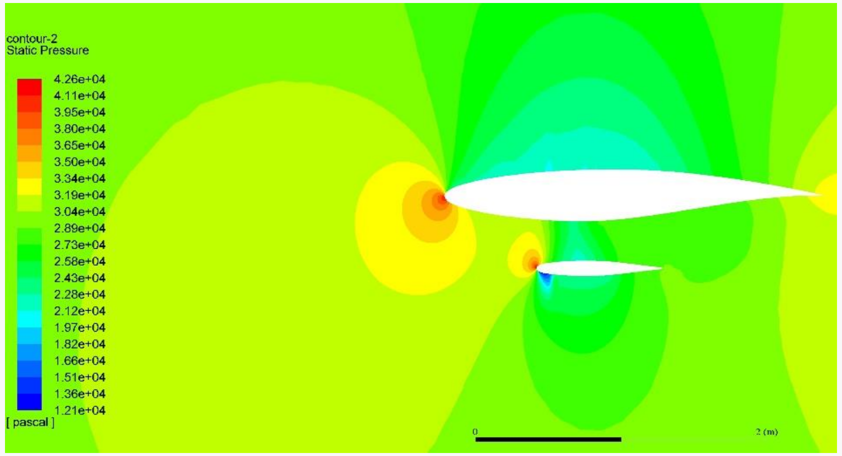


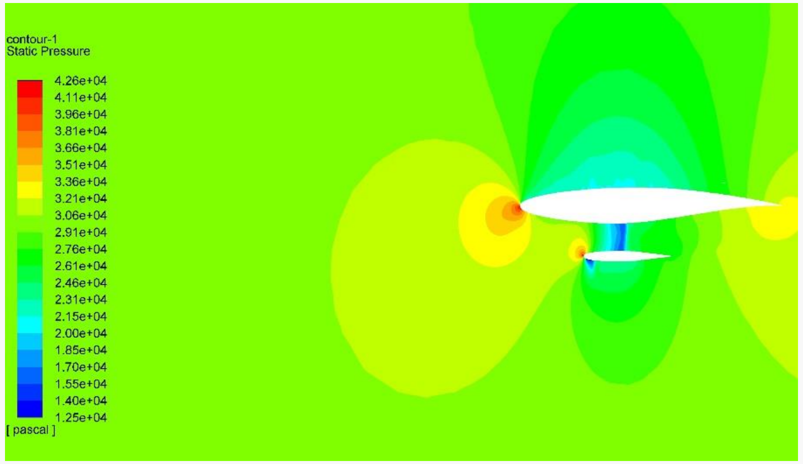



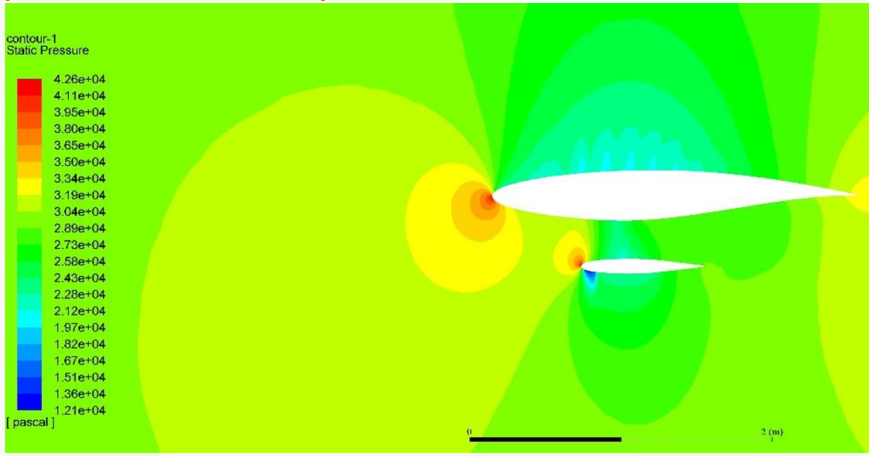




Y slice =16.5m

Massive separation SCB; separation for KC but smaller



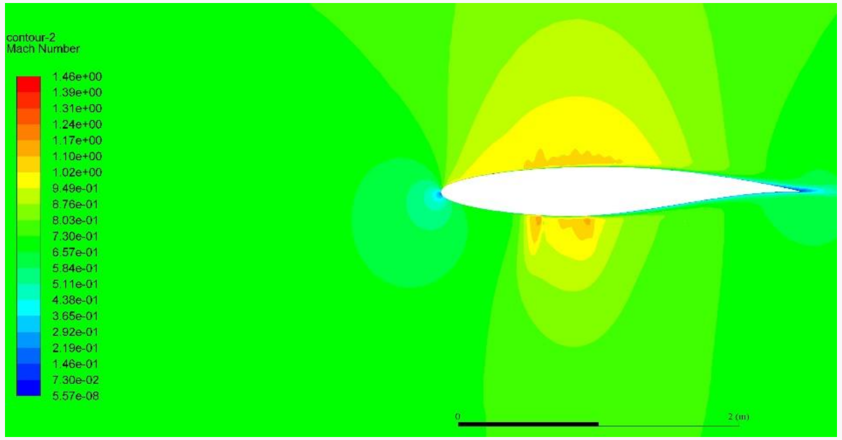



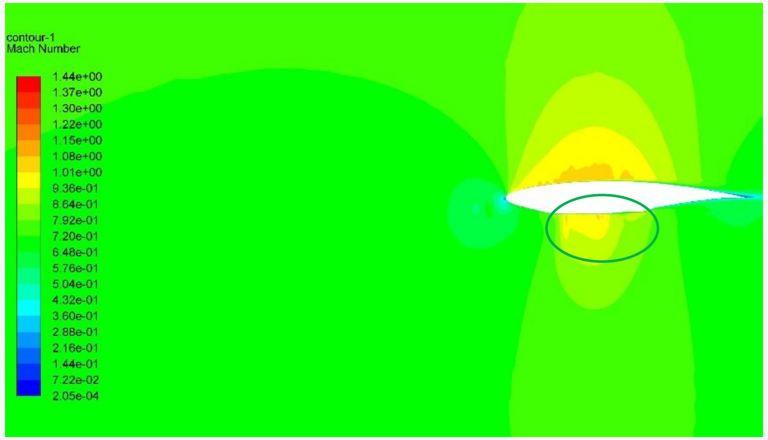



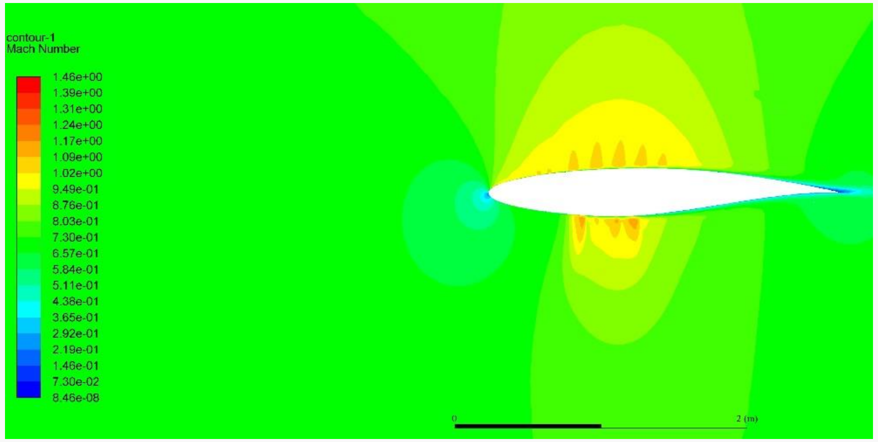
# Results

INCAS
National Institute for Aerospace Research "Elie Carafoli"

| Baseline | Kuchemann Carrot | Shock Control Bump |
|---|---|---|

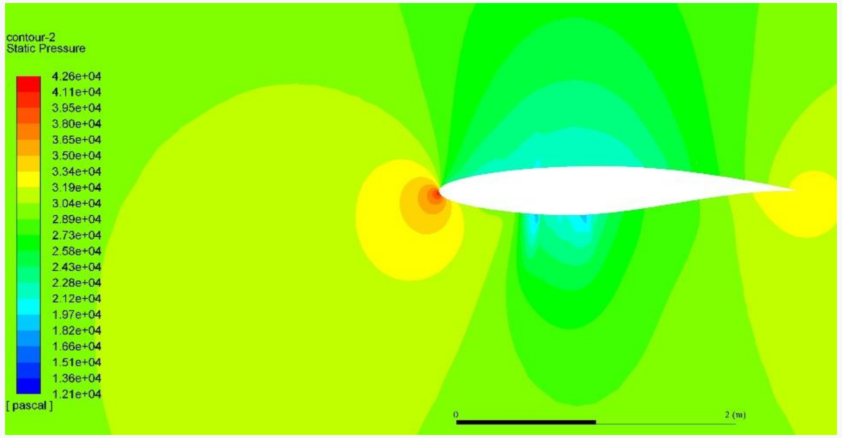


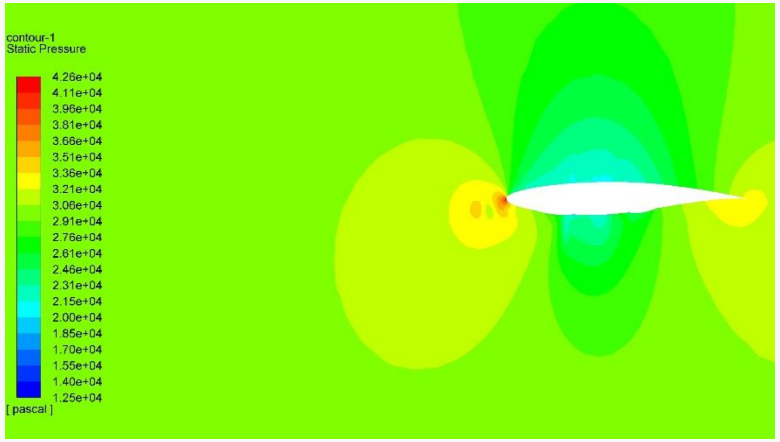



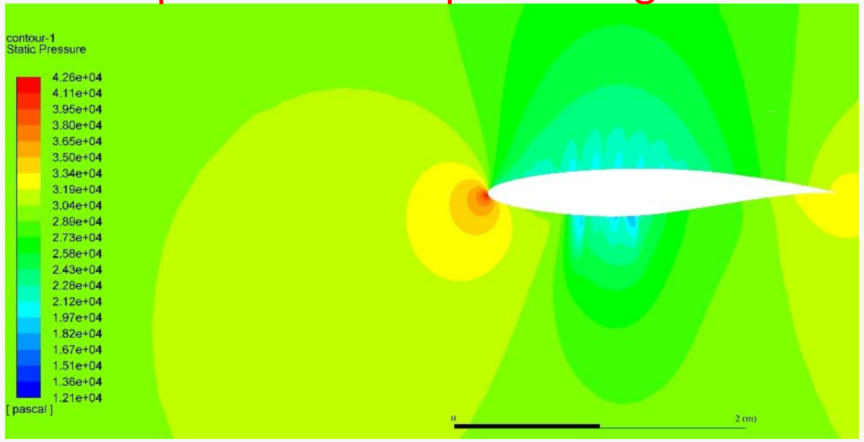




Y slice =16.8m

Less increased speed on outer panel wing KC



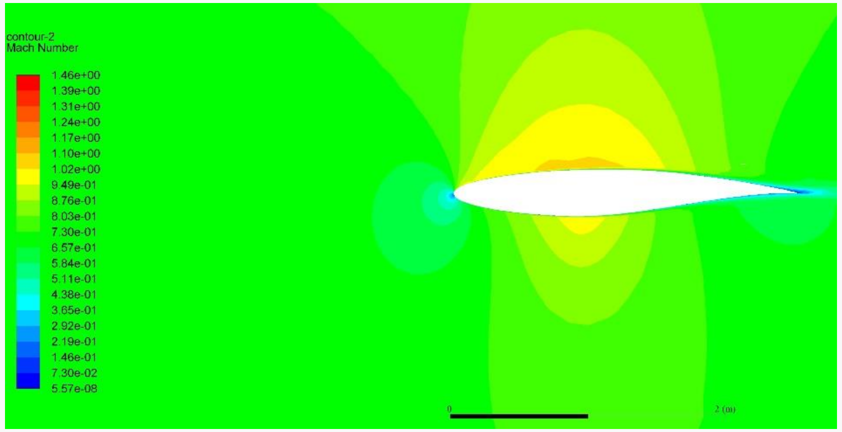



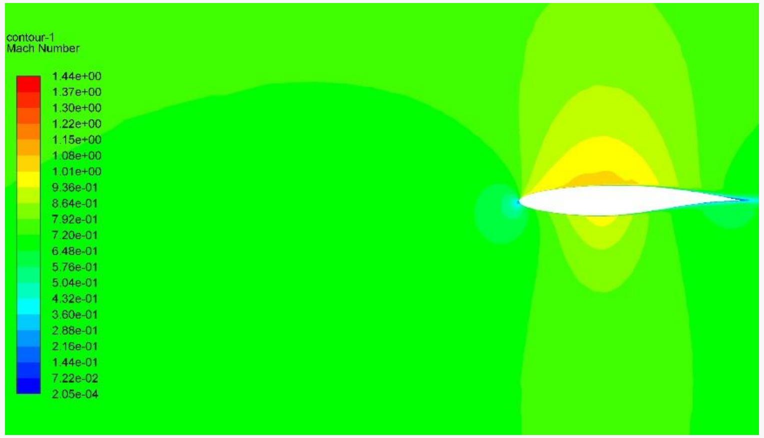



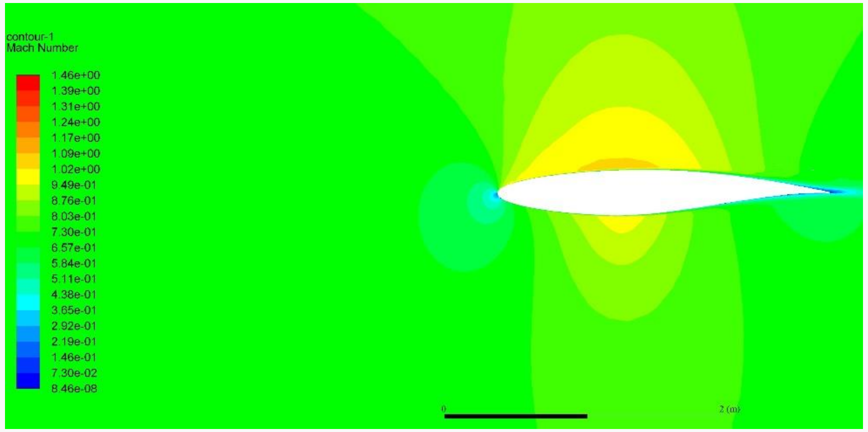
# Results

National Institute for Aerospace Research "Elie Carafoli"

| Baseline | Kuchemann Carrot | Shock Control Bump |
|---|---|---|

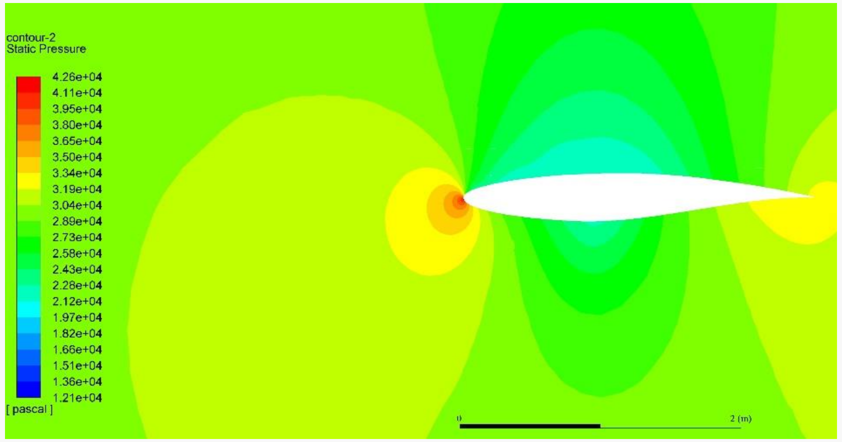


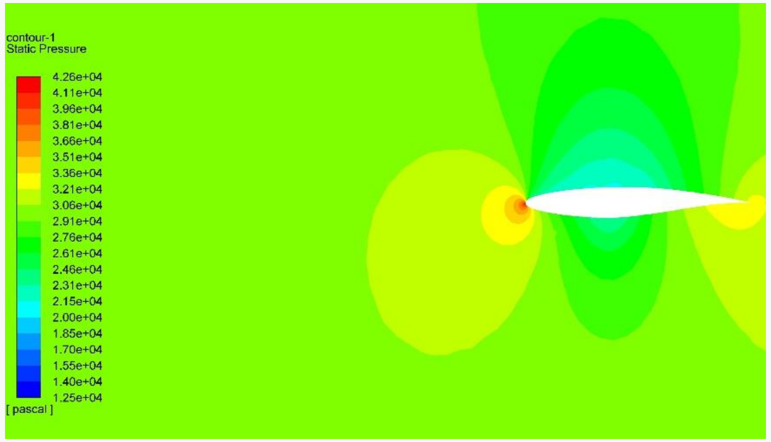



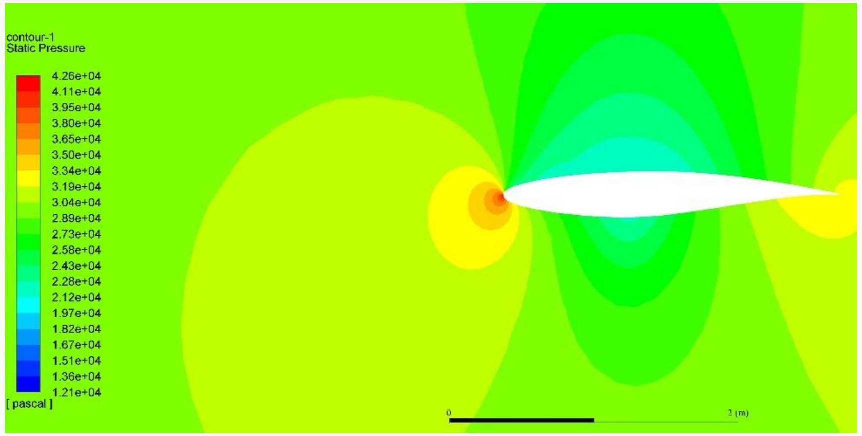




Y slice =17.3m

Little / No difference

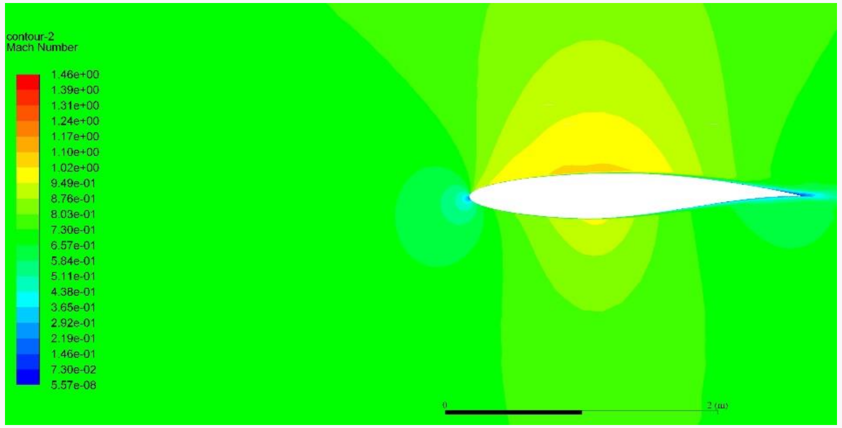


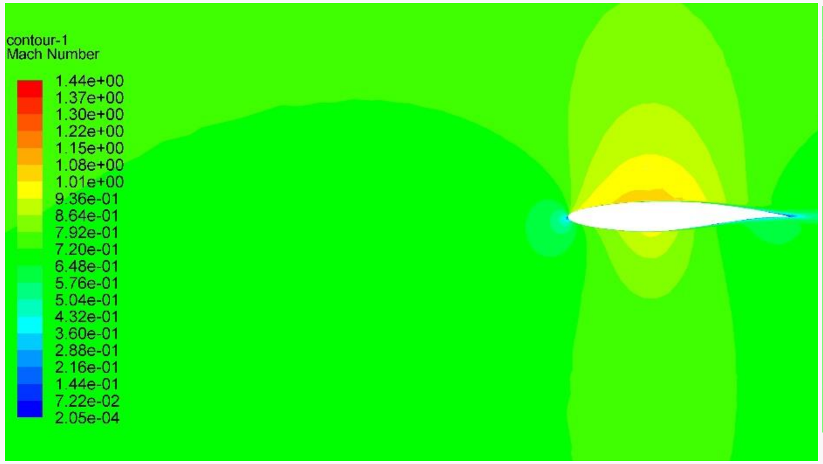



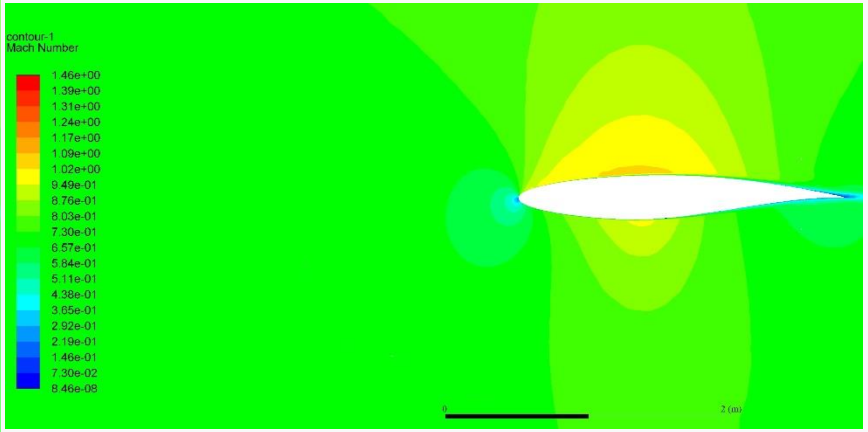



# Results

| Baseline | Kuchemann Carrot | Shock Control Bump |
|---|---|---|

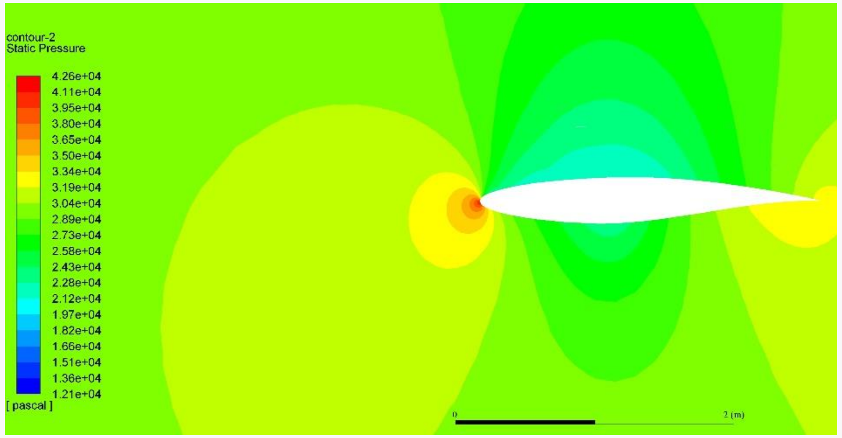


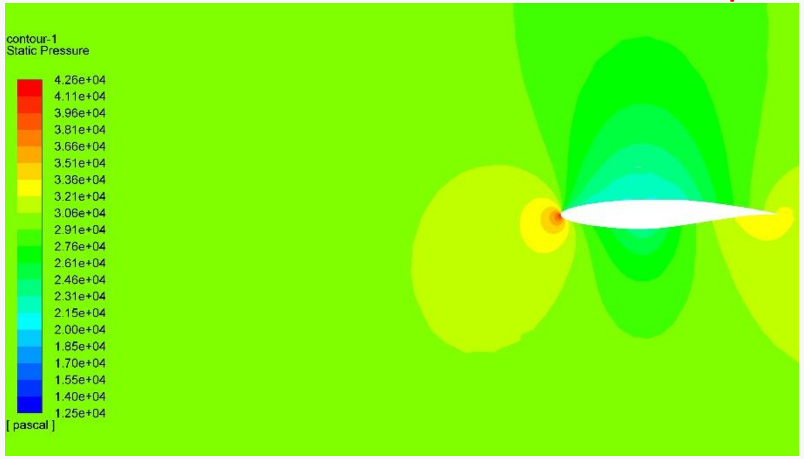



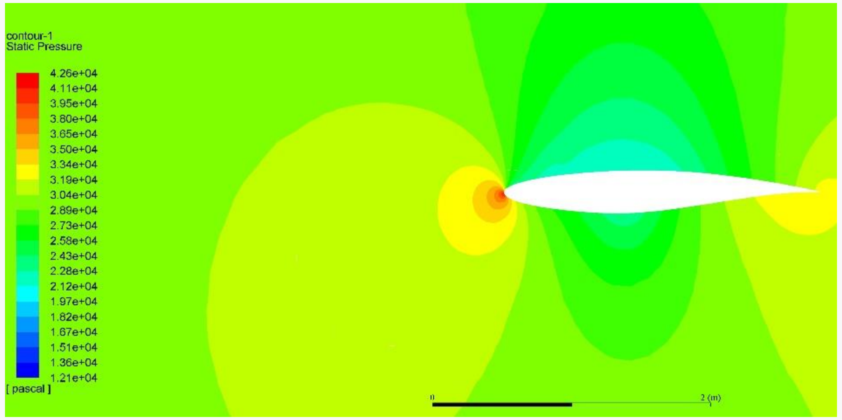




Y slice =17.8m

Little / No difference

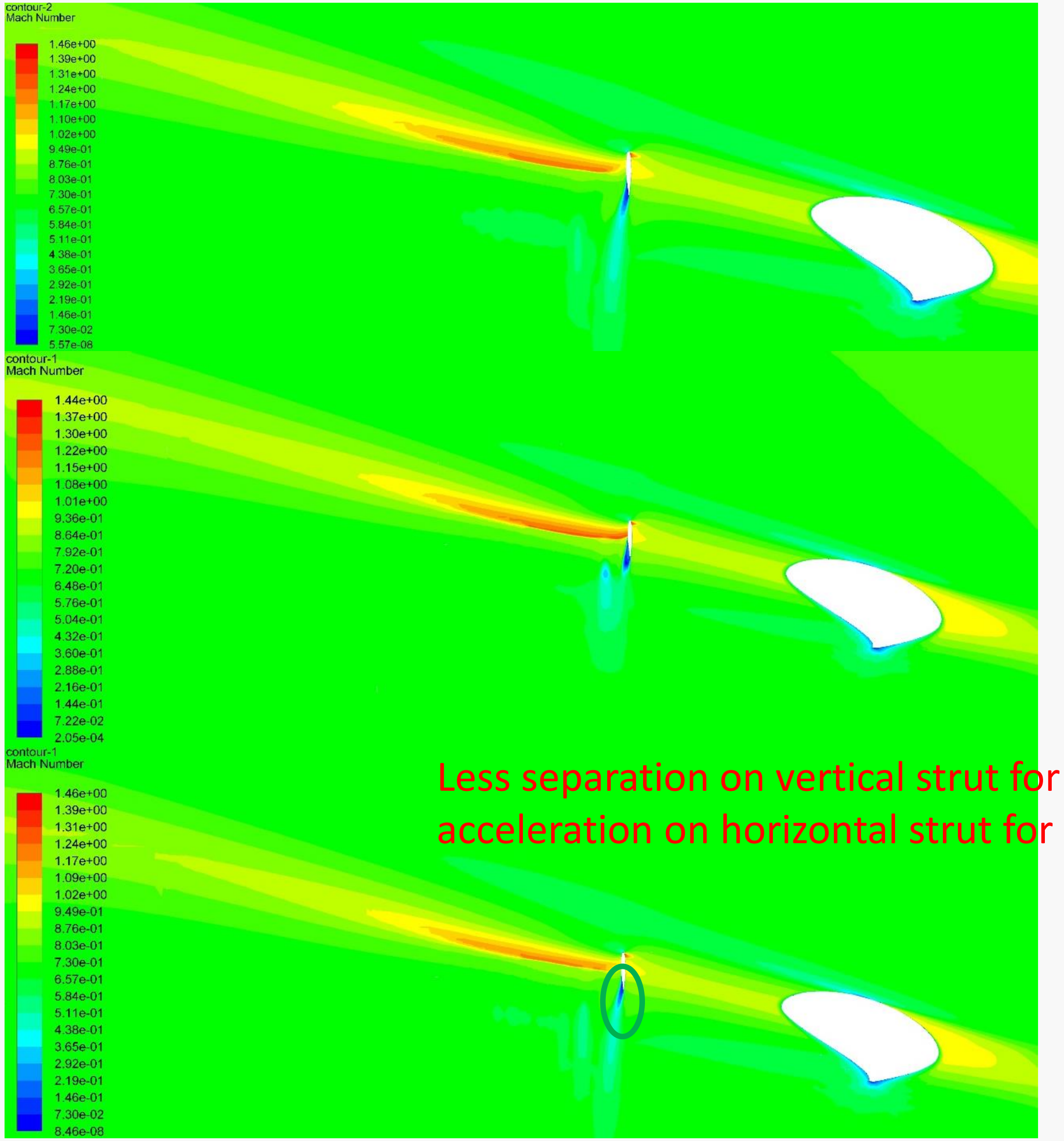


# Results

Z slice =0.87m

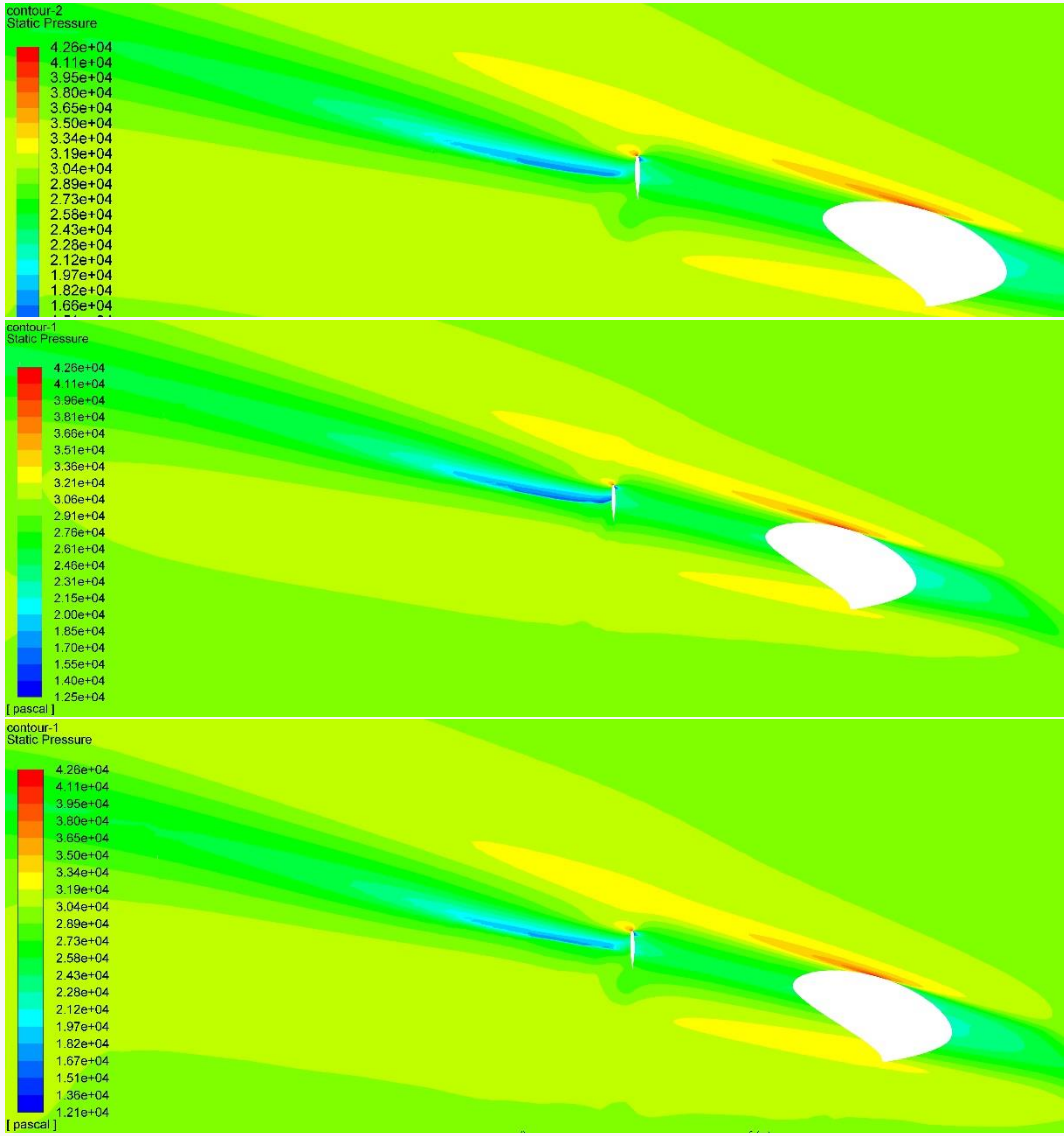



Baseline

Kuchemann Carrot

Less separation on vertical strut for SCB and less acceleration on horizontal strut for SCB

Shock Control Bump



# Results

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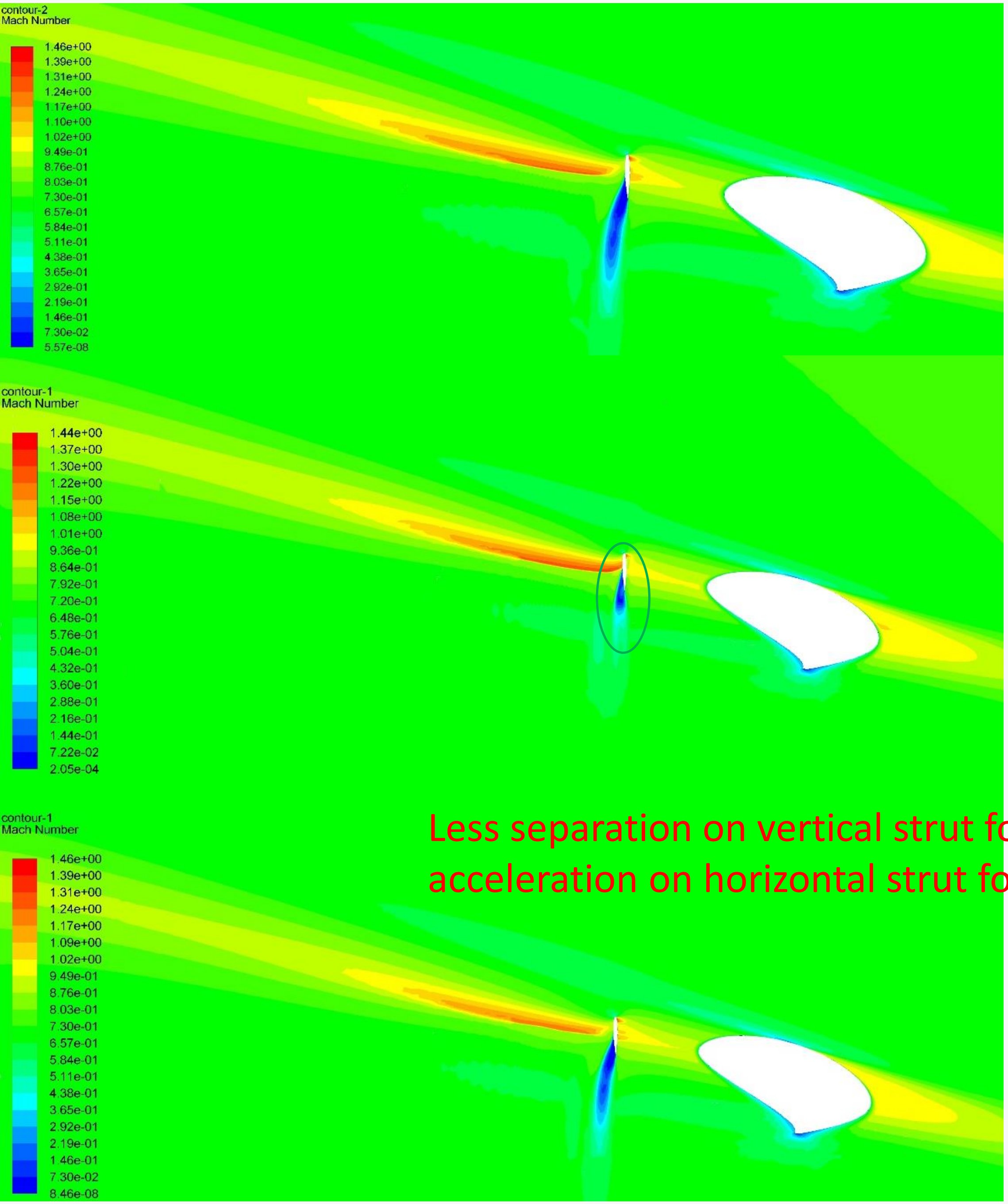
Z slice =0.97m

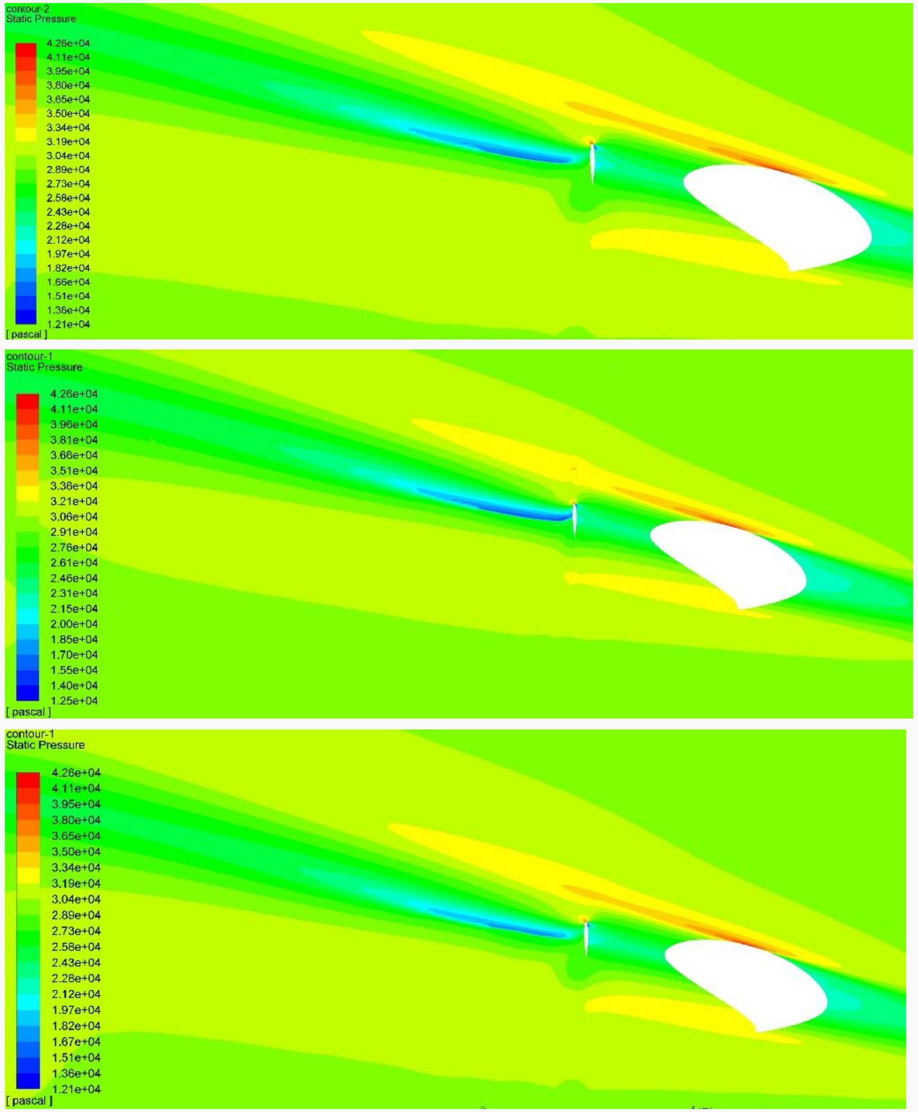



Baseline

Kuchemann Carrot

Less separation on vertical strut for KC and less acceleration on horizontal strut for SCB

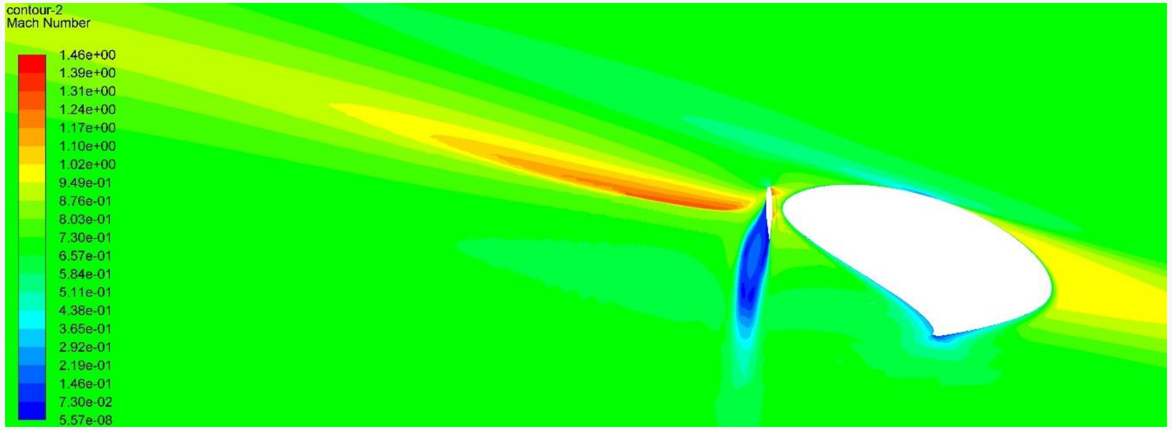
Shock Control Bump

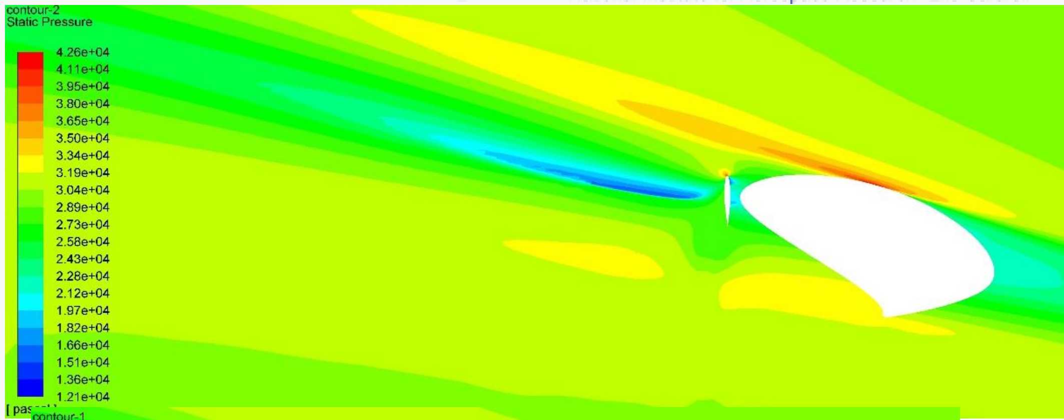


# Results

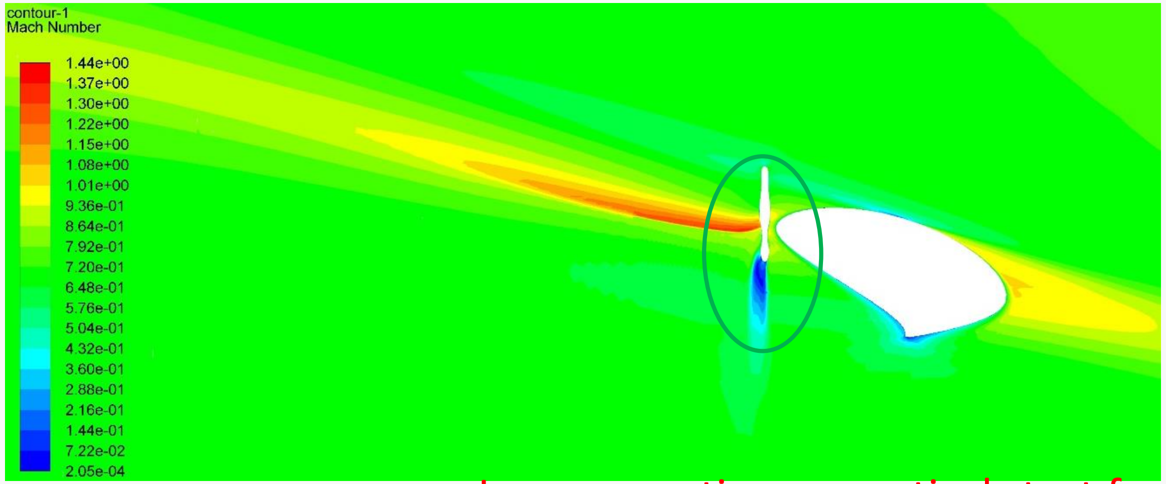
Z slice =1.07m

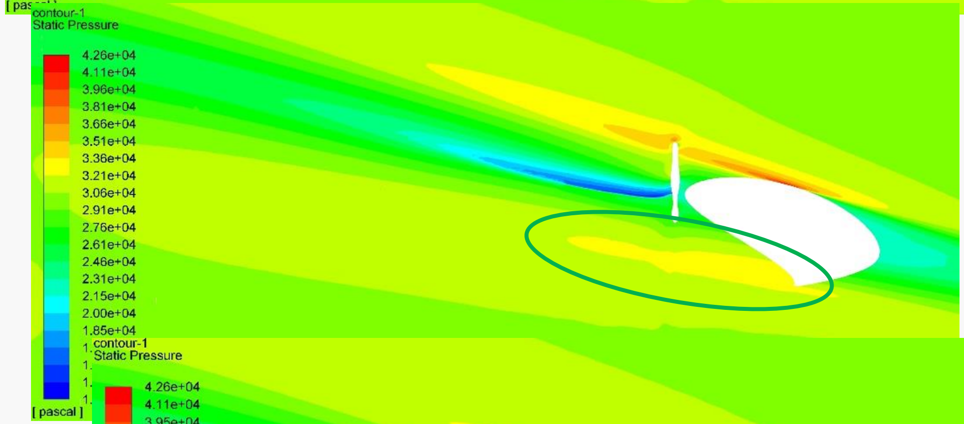
Baseline



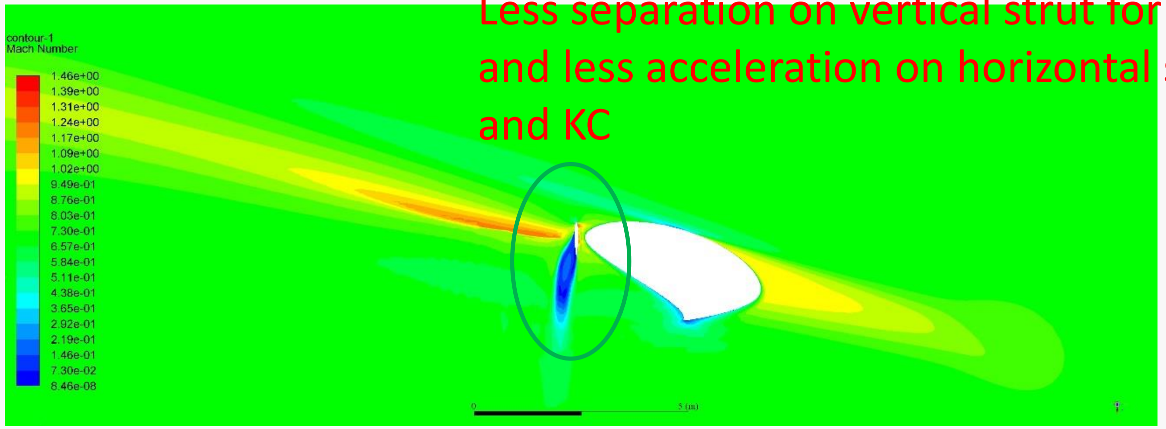

Kuchemann Carrot

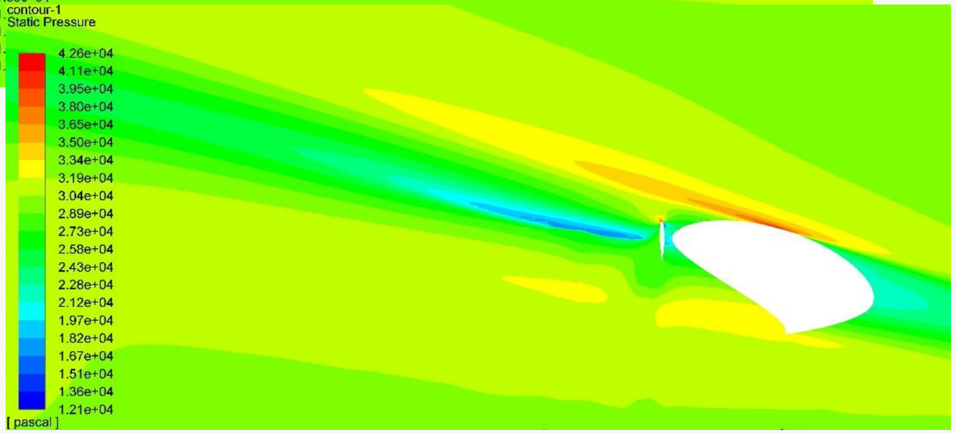


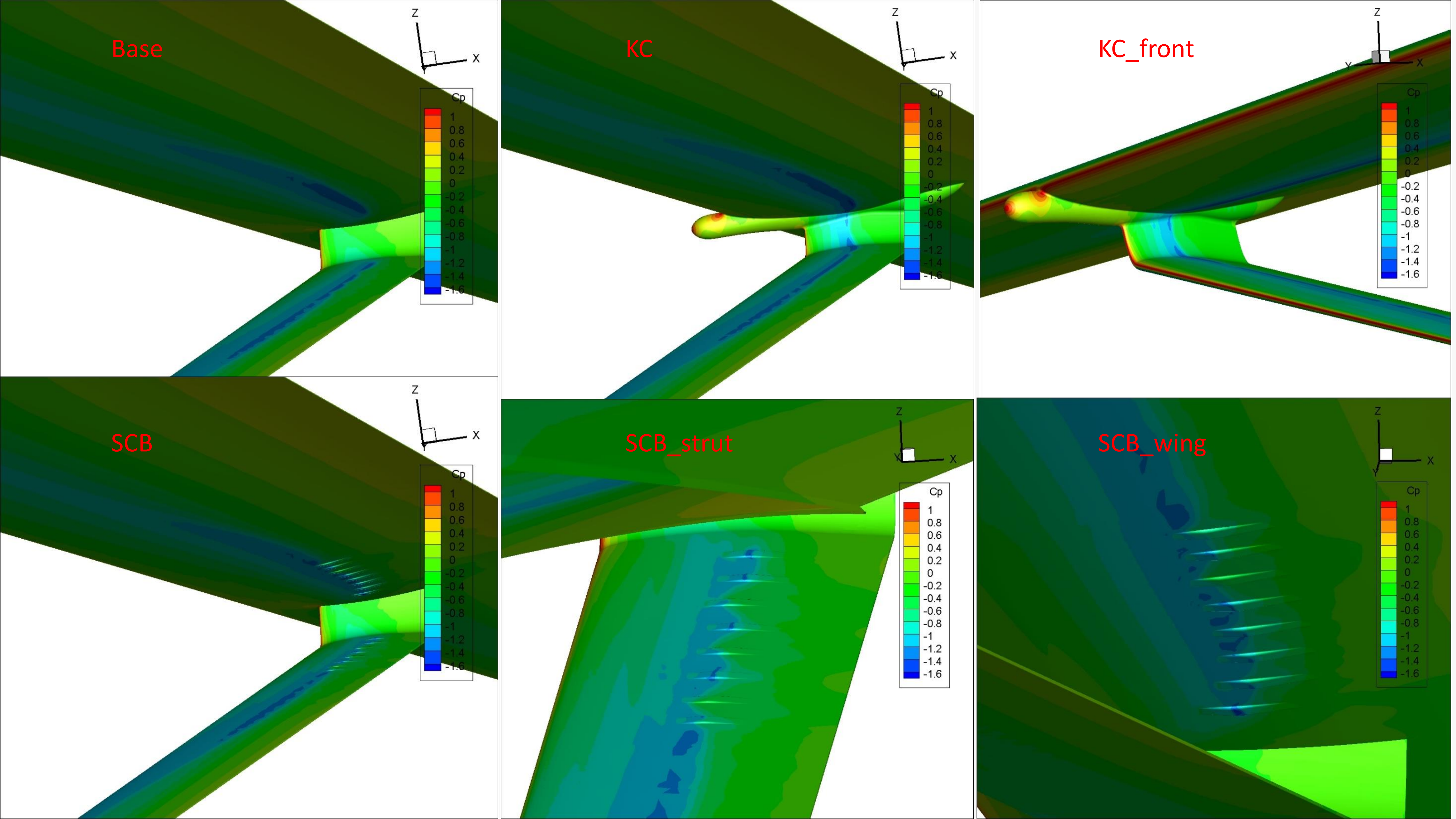




Less separation on vertical strut for KC and SCB and less acceleration on horizontal strut for SCB and KC

Shock Control Bump



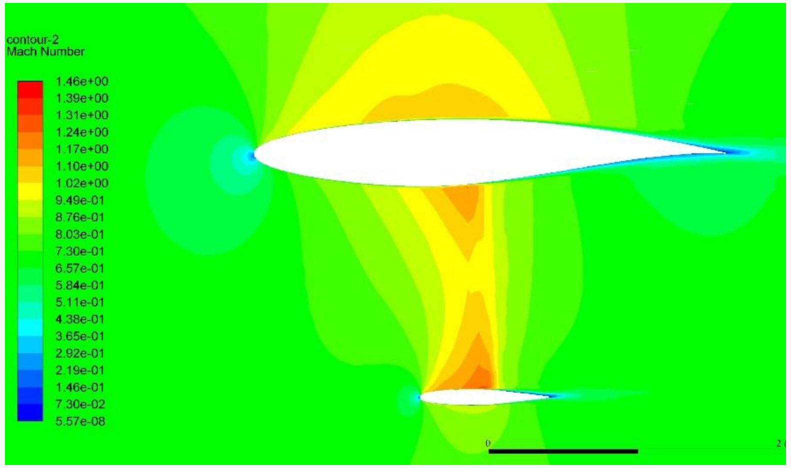



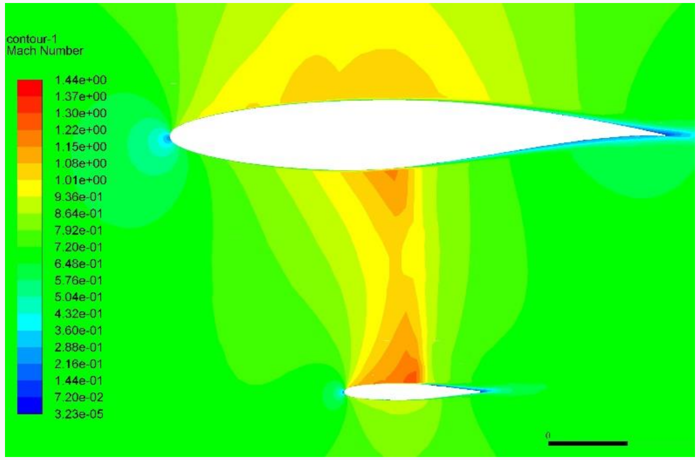

Base
KC
KC_front
SCB
SCB_strut
SCB_wing
Cp
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
Z
X
Y

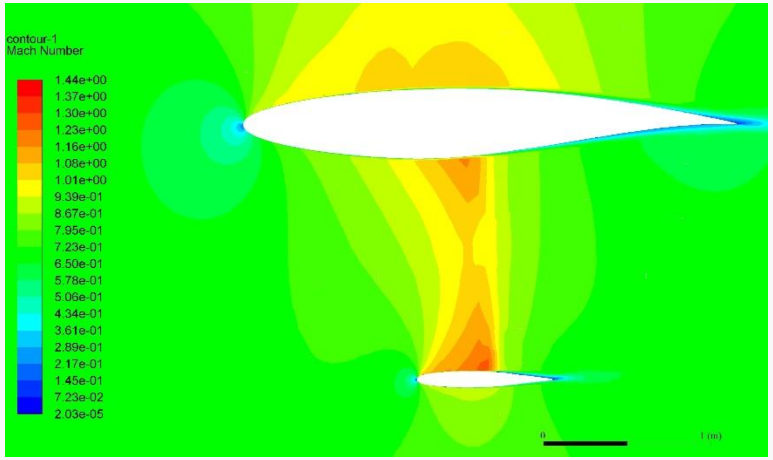
# Results



Baseline | KC-SCB_v0 | KC-SCB_v2

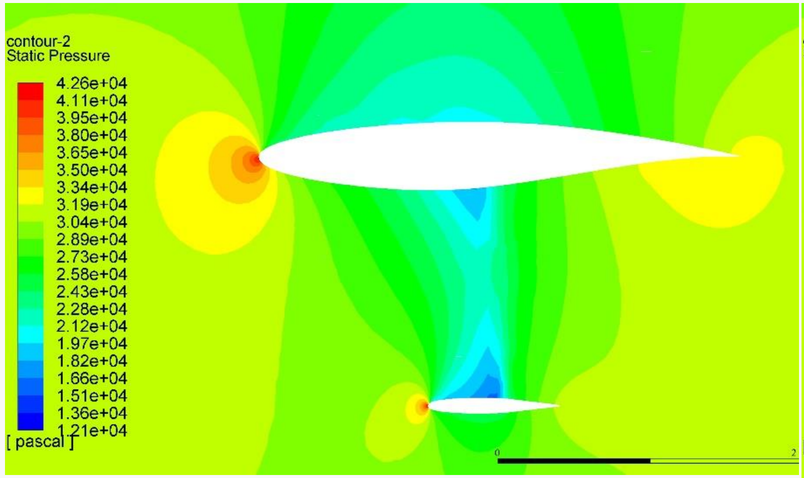


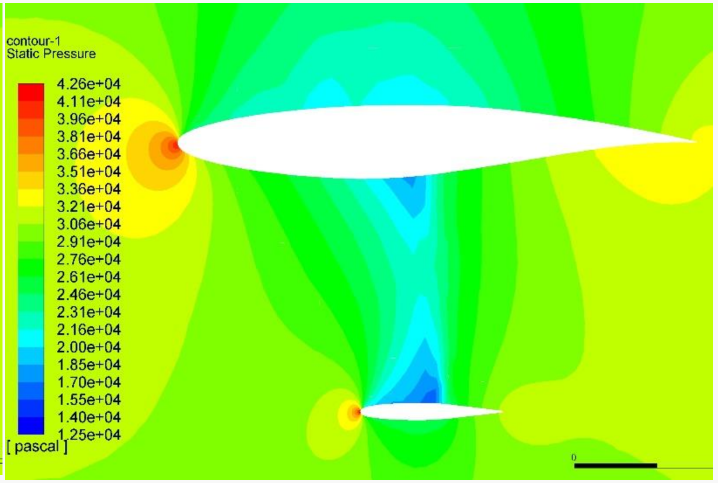



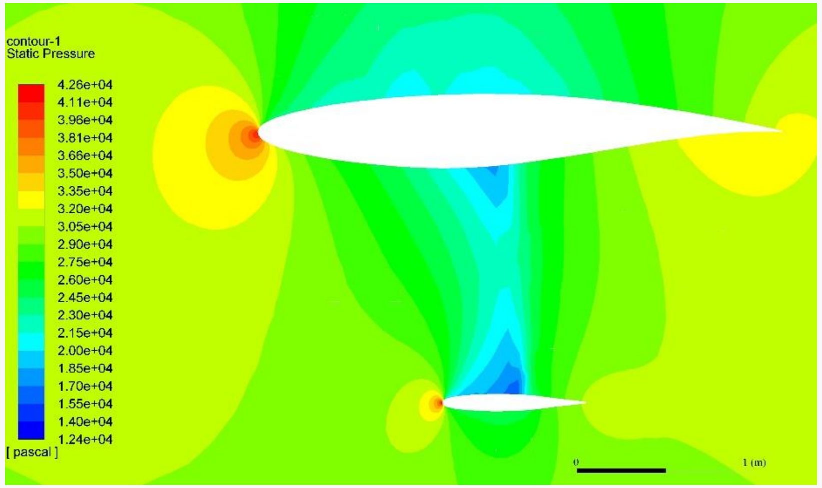




Y slice =12m

Little / No difference



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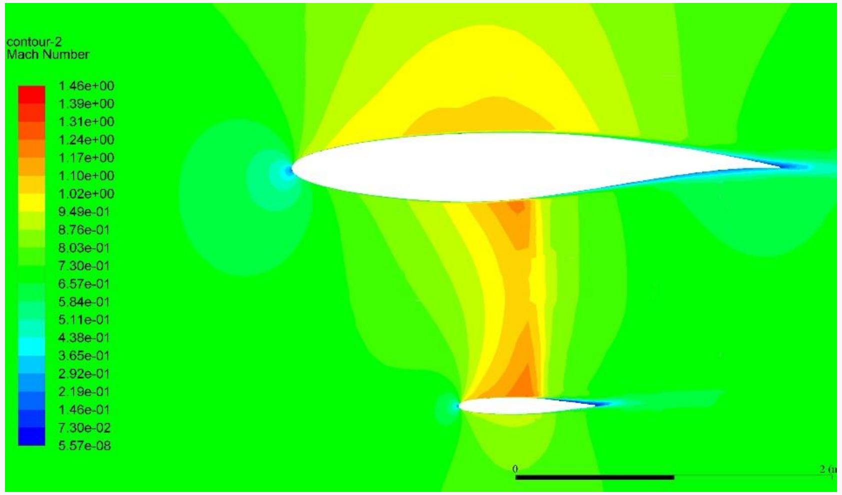
National Institute for Aerospace Research "Elie Carafoli"

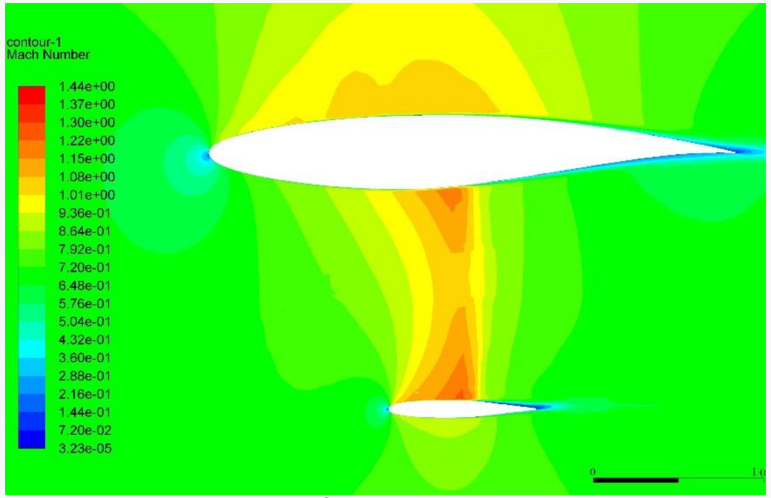
# Results

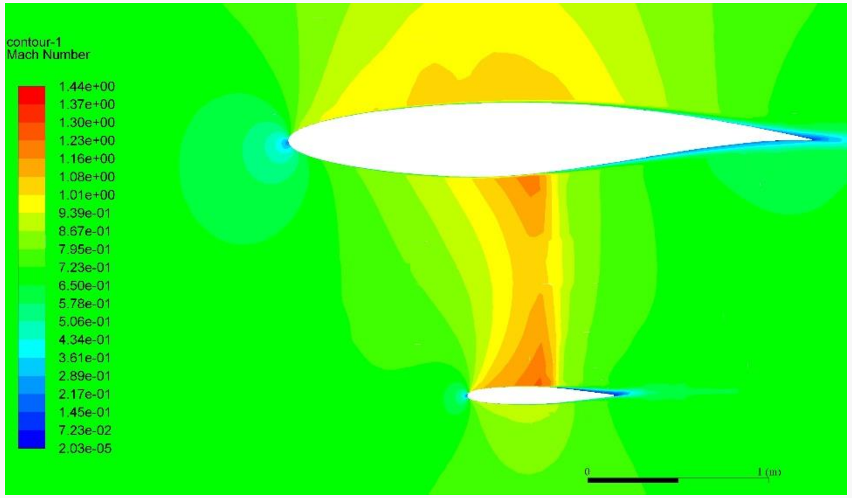
Baseline

KC-SCB_v0

KC-SCB_v2

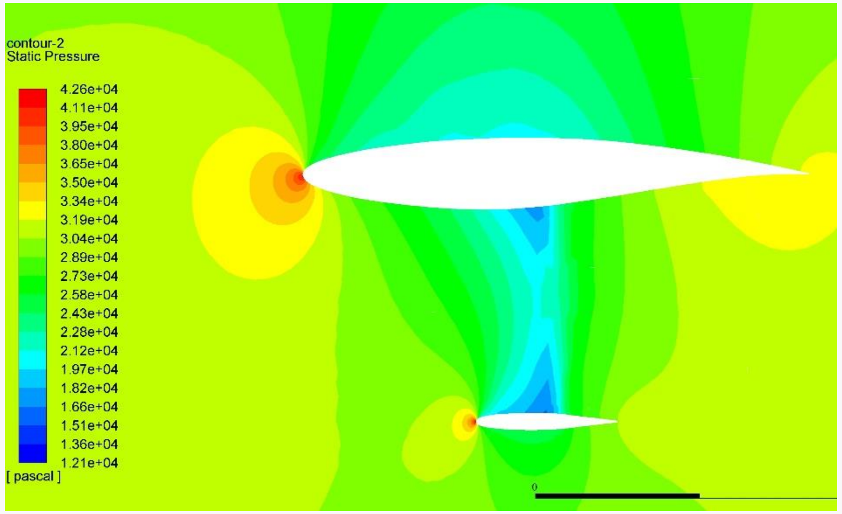


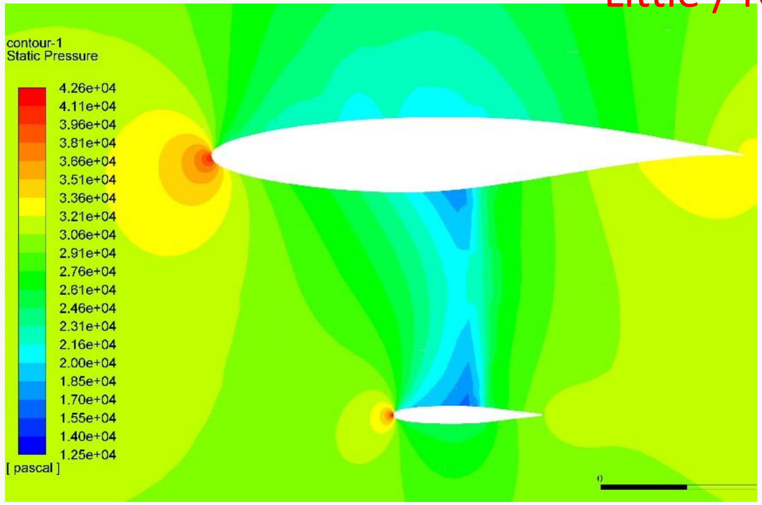



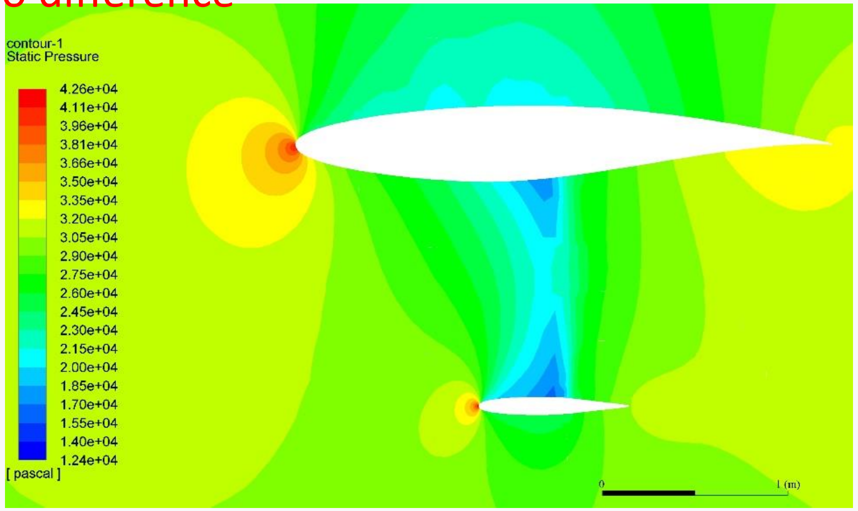




Y slice =12.5m

Little / No difference



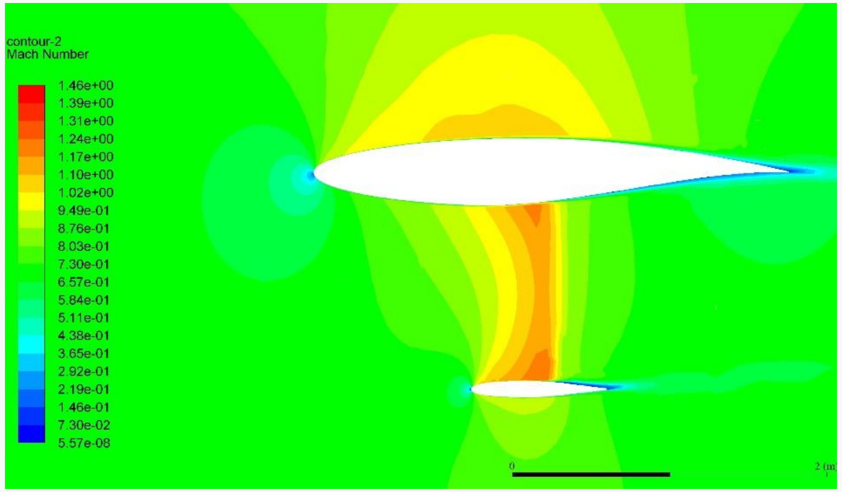



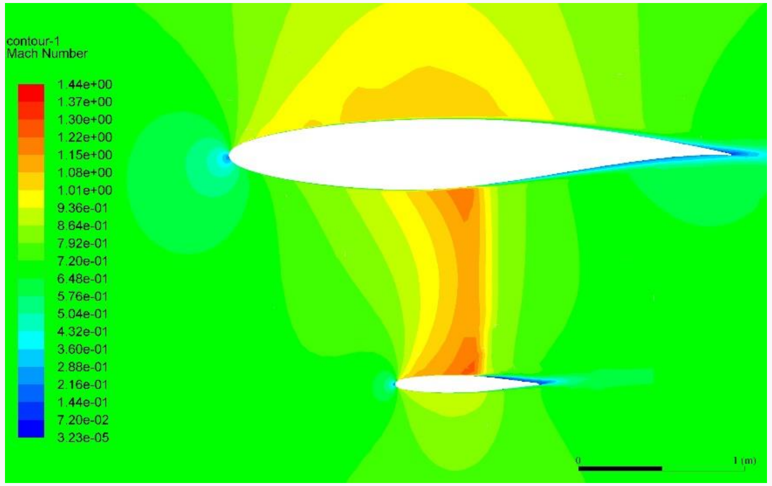



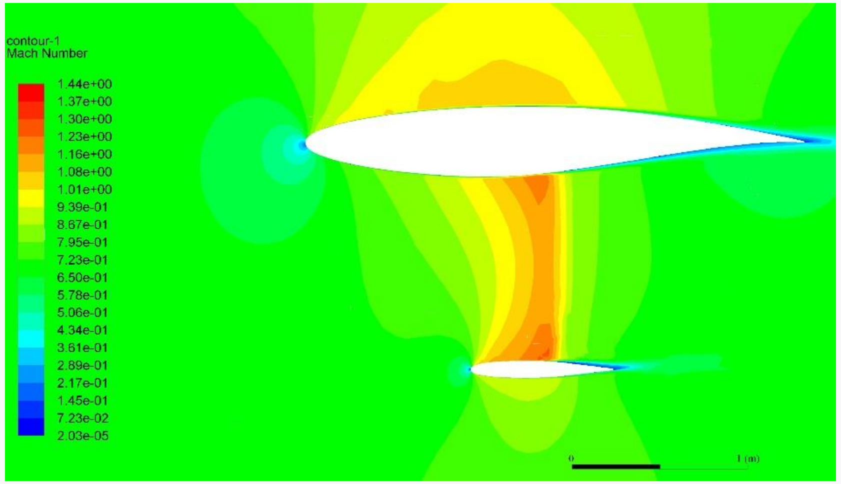
# Results

National Institute for Aerospace Research "Elie Carafoli"

Baseline | KC-SCB_v0 | KC-SCB_v2

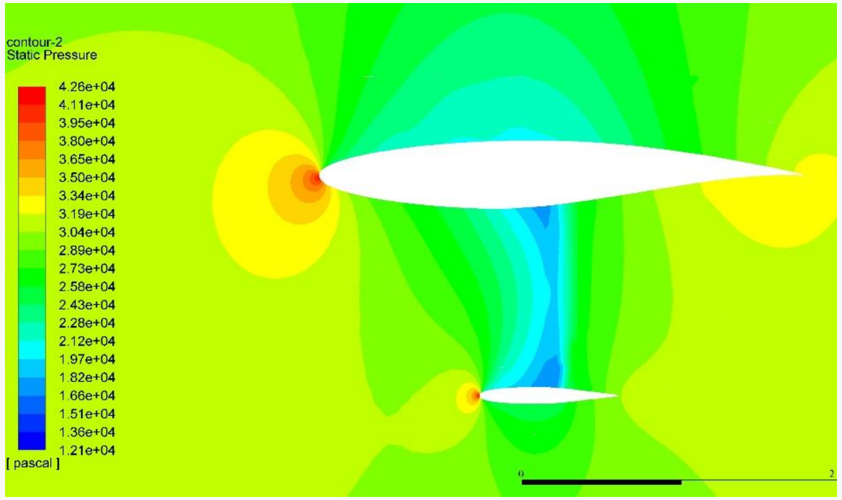


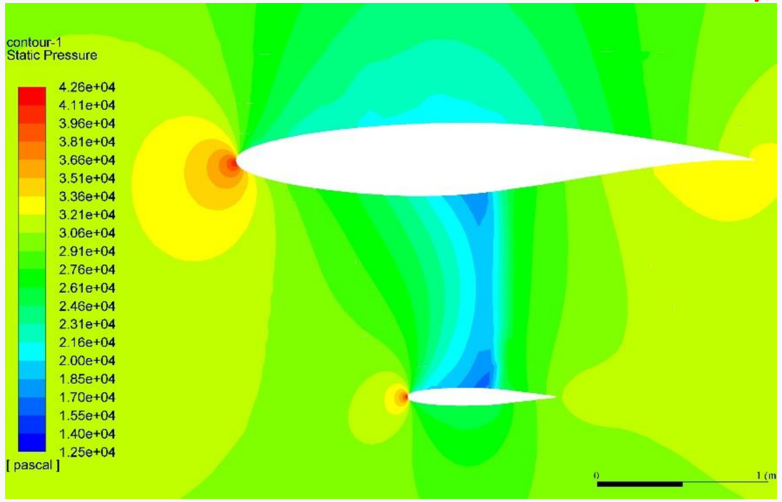



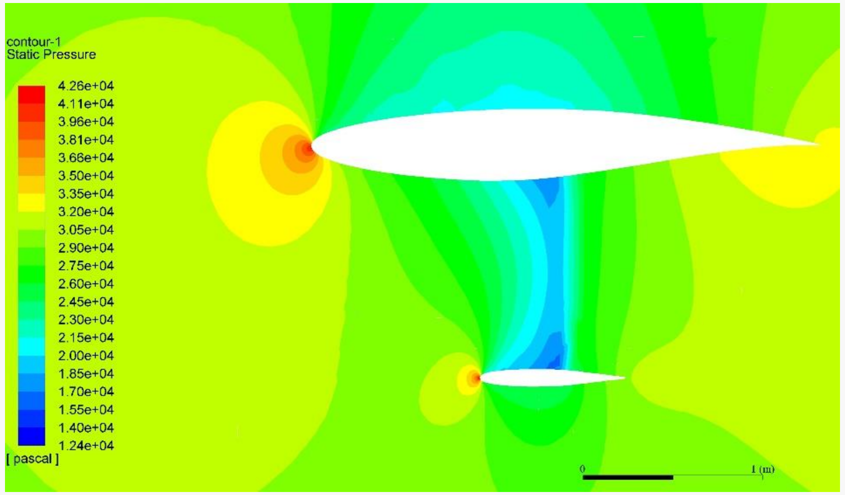




Y slice =13m

Little / No difference

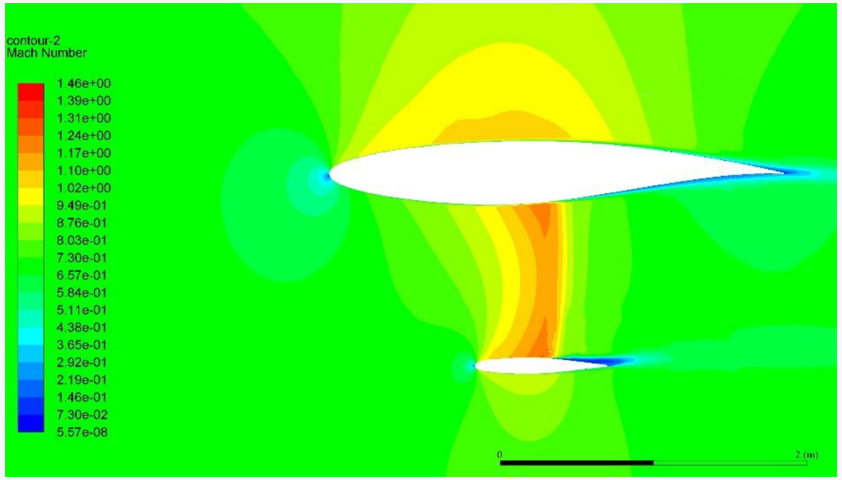


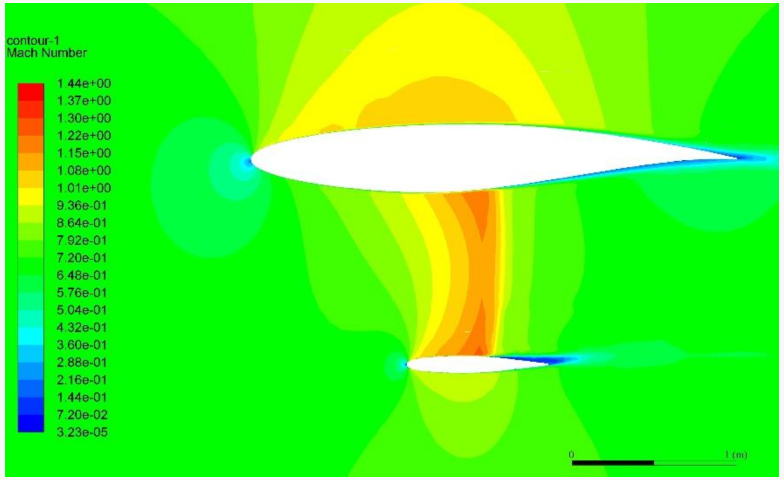



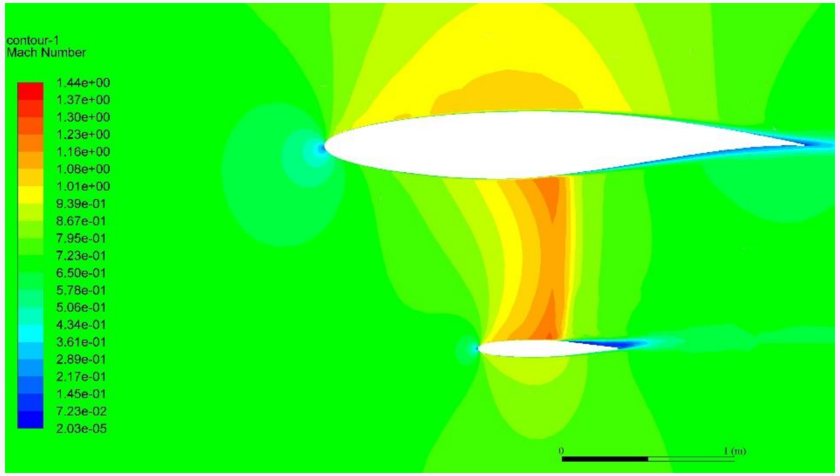



# Results

| Baseline | KC-SCB_v0 | KC-SCB_v2 |
|---|---|---|

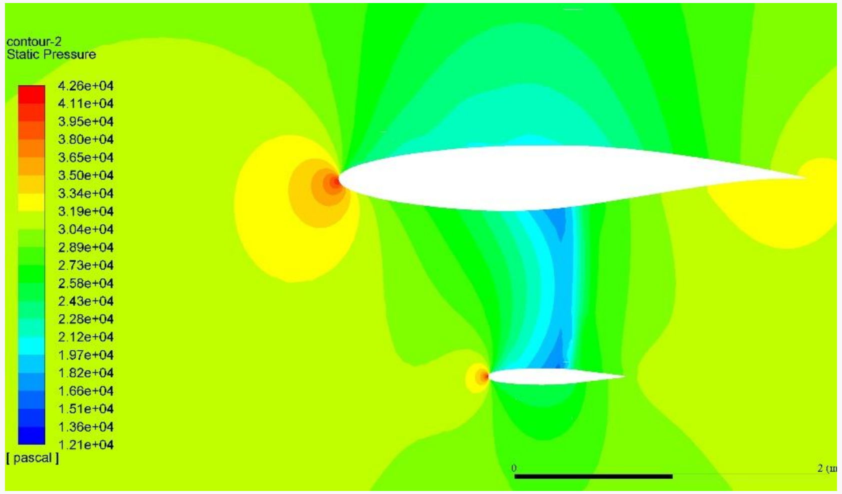


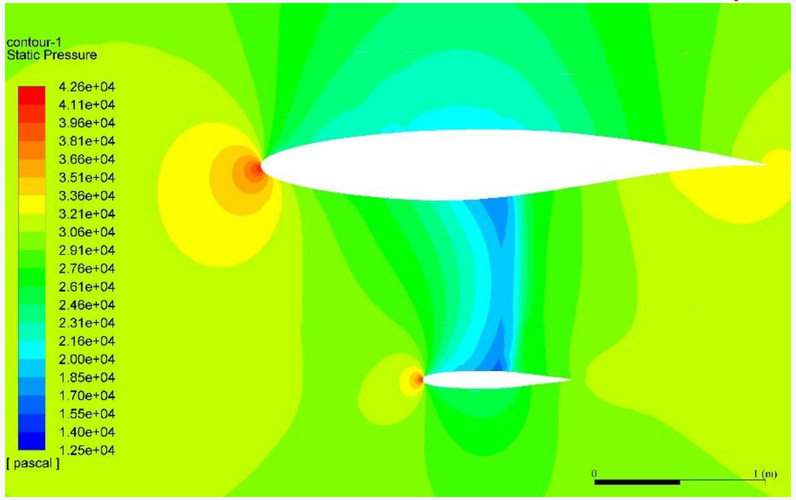



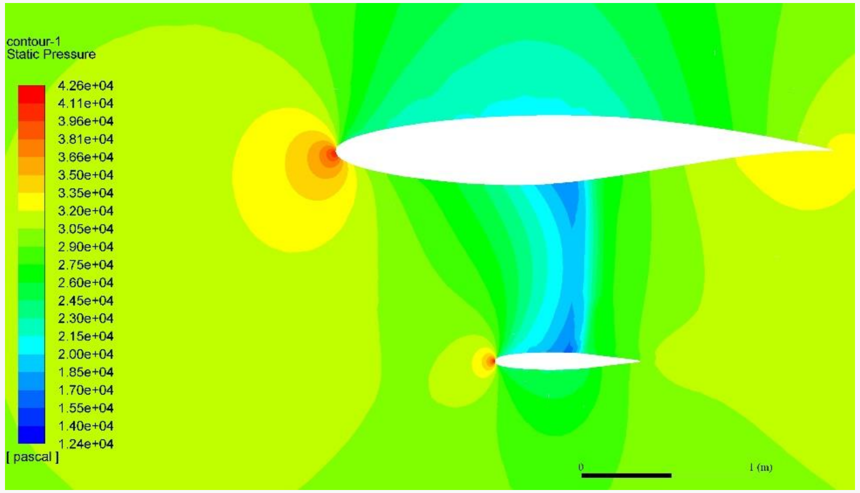




Y slice =13.5m

Little / No difference

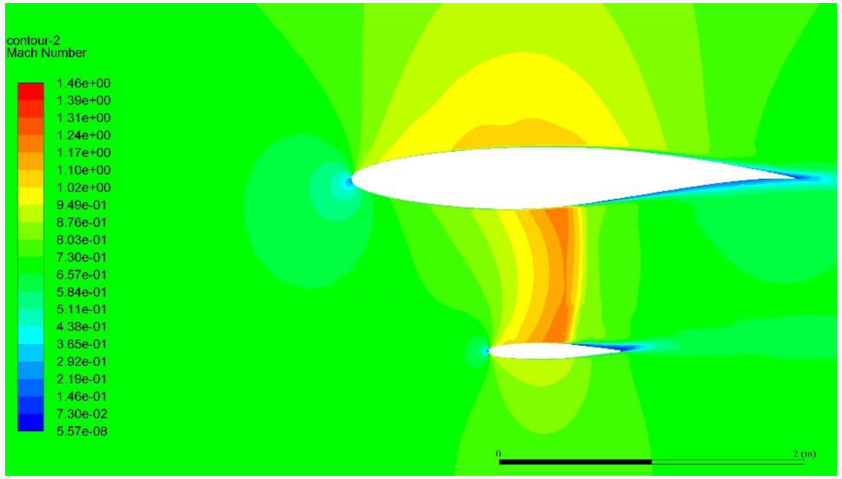


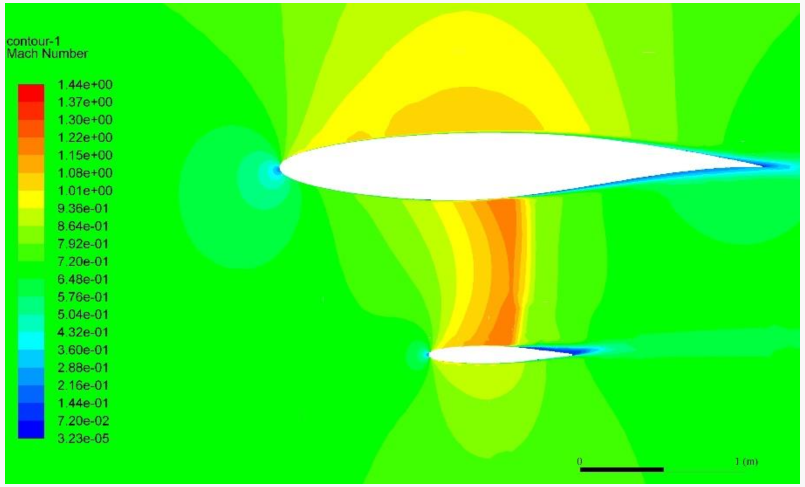



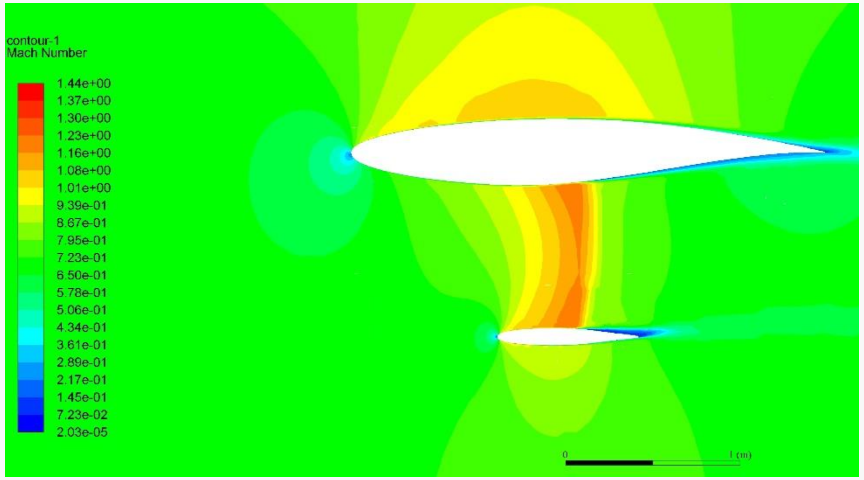



# Results

Baseline | KC-SCB_v0 | KC-SCB_v2

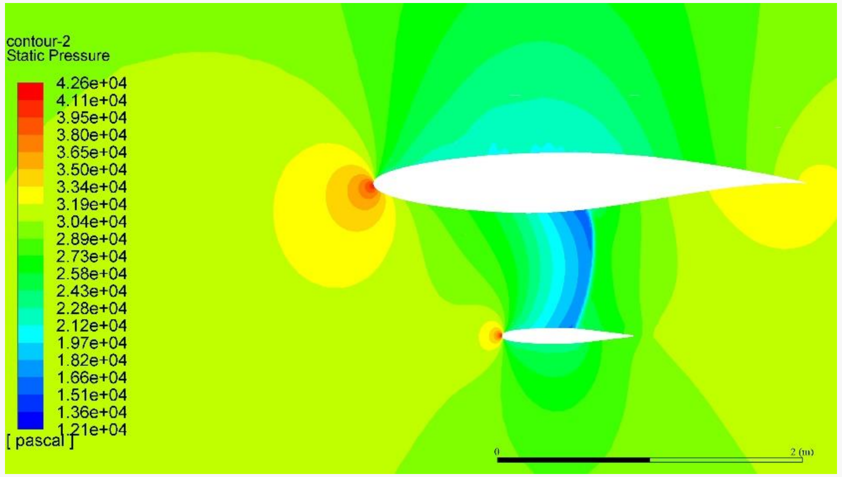


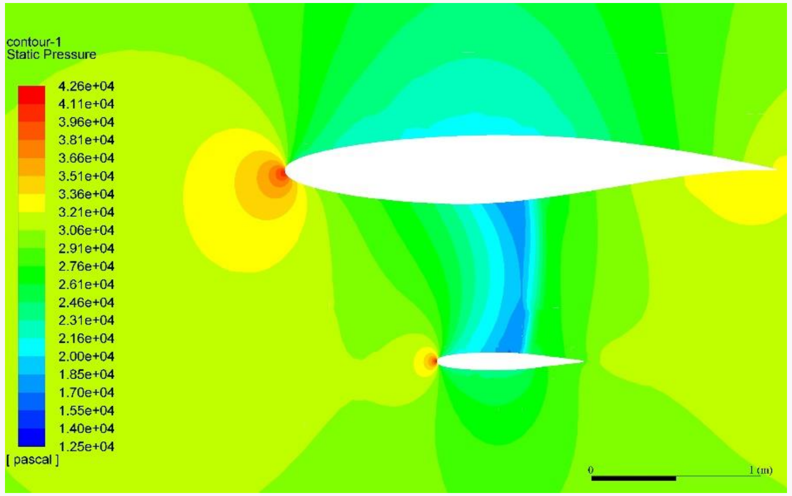



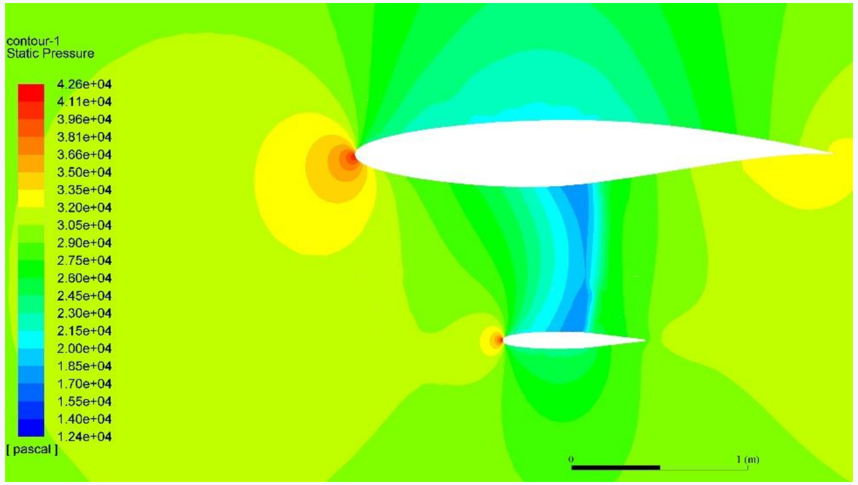




Y slice =14m

Little / No difference

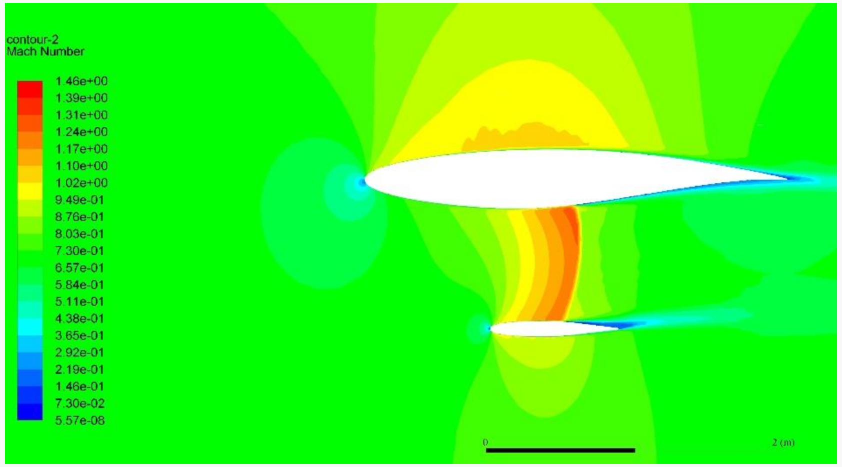


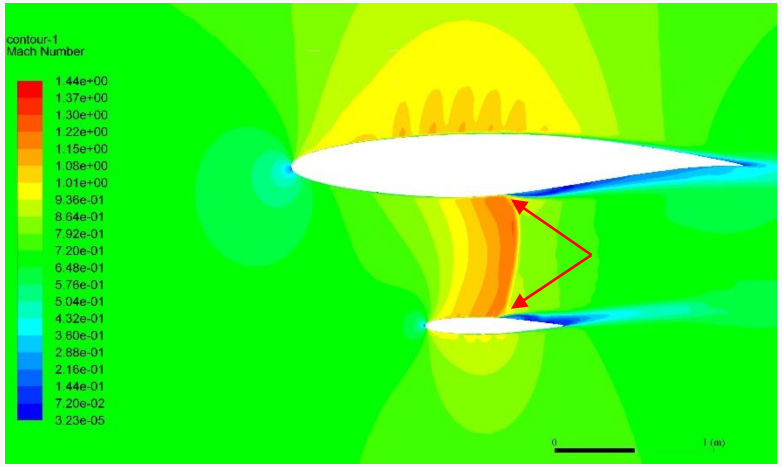



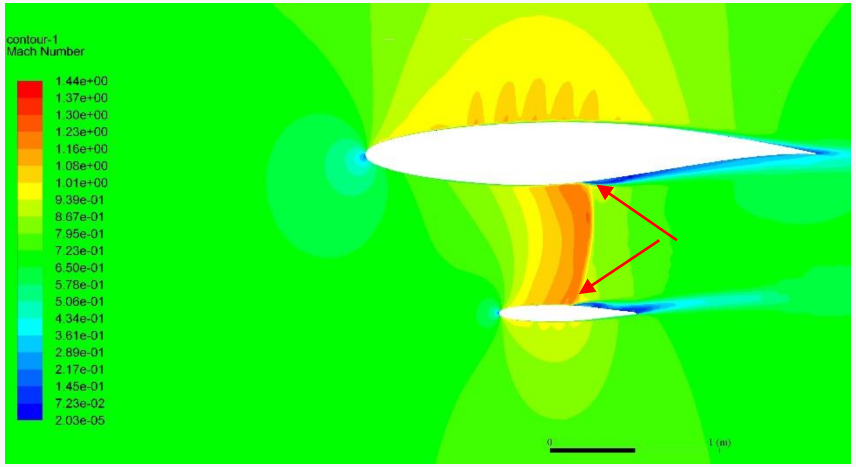



# Results

Baseline | KC-SCB_v0 | KC-SCB_v2

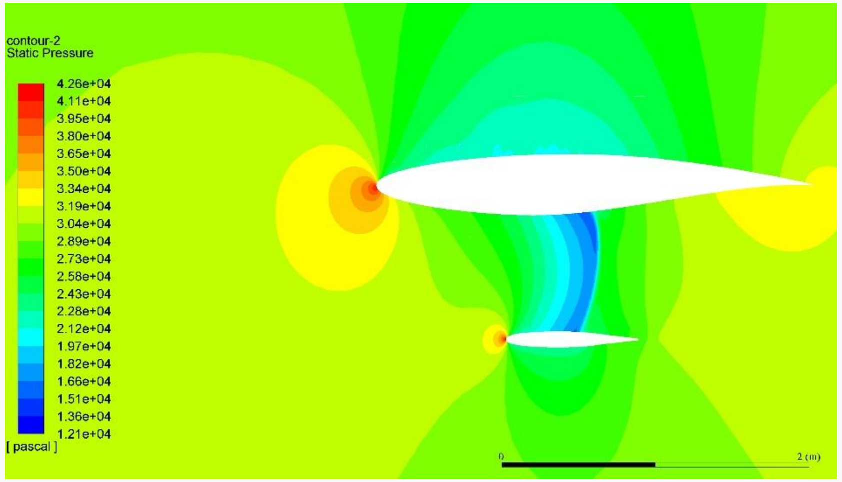


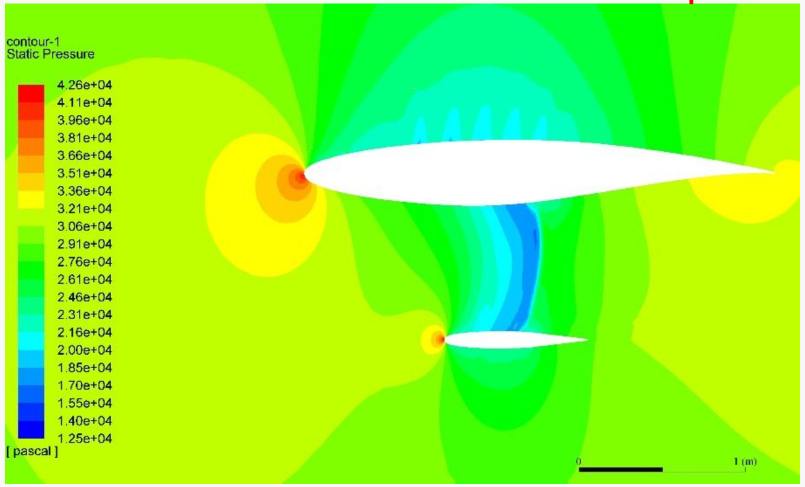



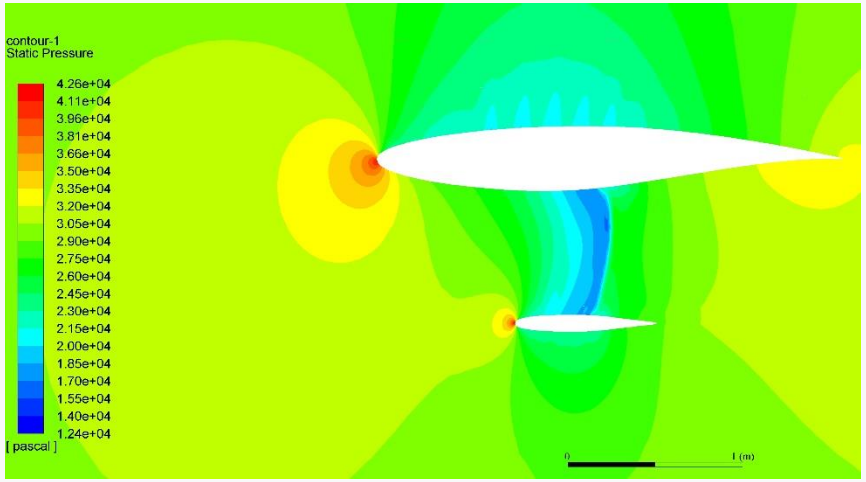




Y slice =14.5m

Separated flow

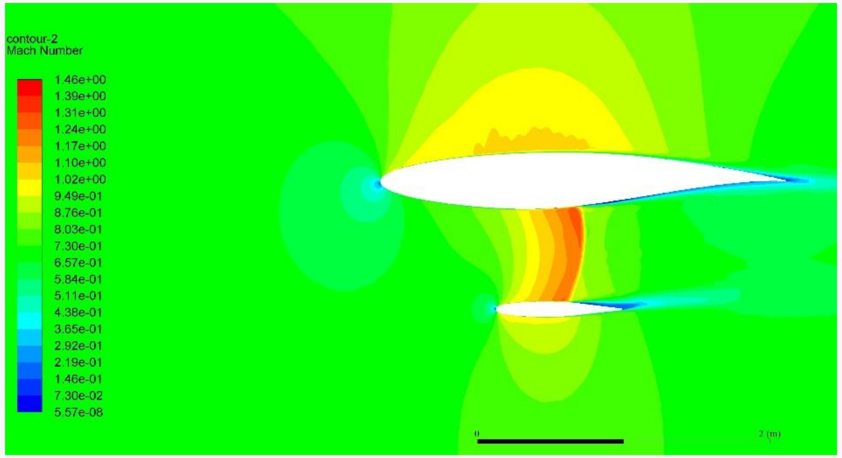


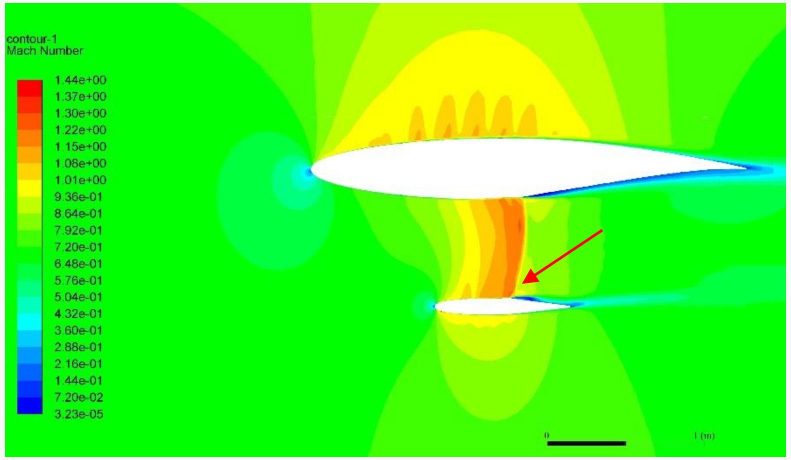



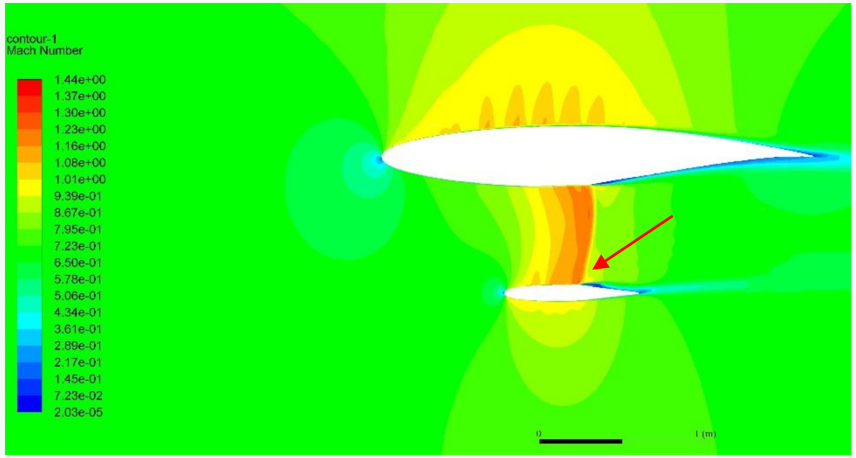



# Results

Baseline | KC-SCB_v0 | KC-SCB_v2

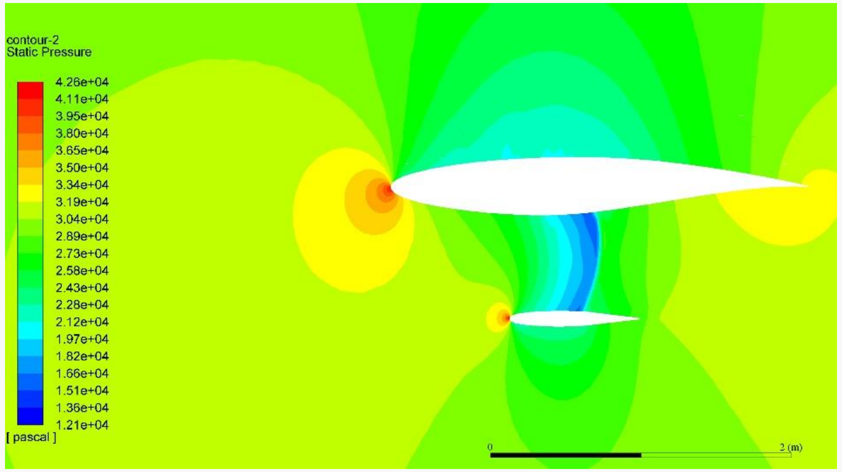


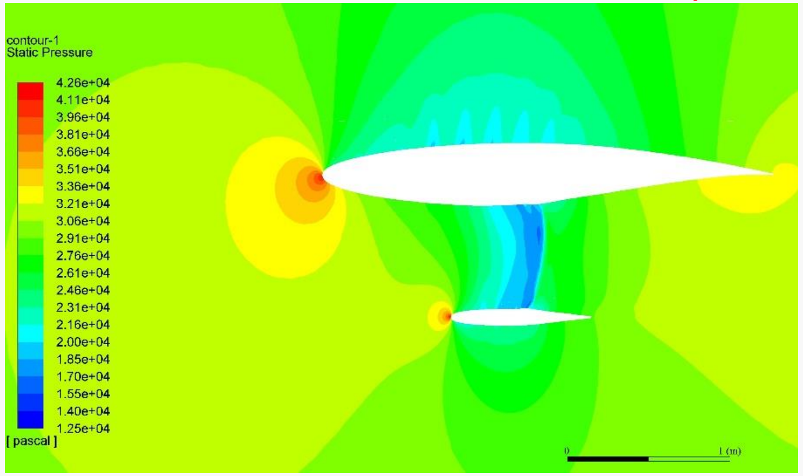



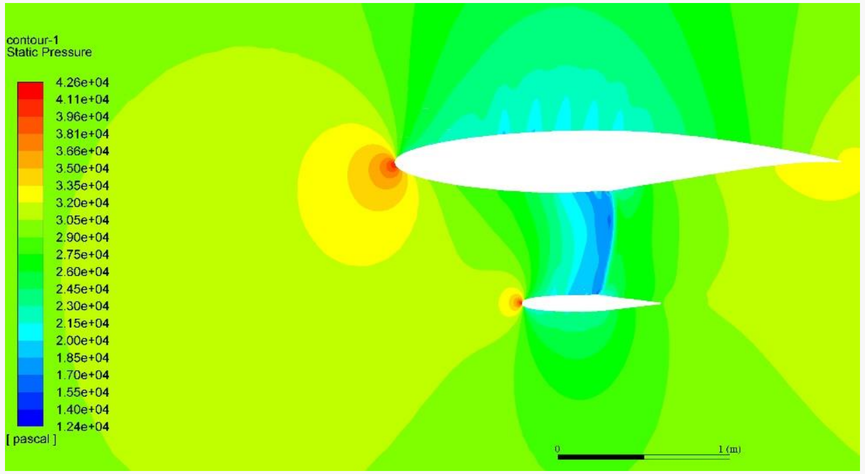




Y slice =15m

Separated flow



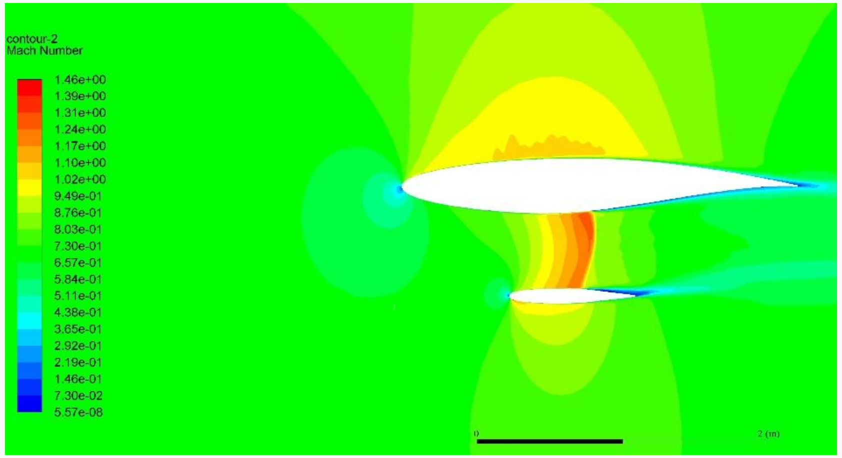



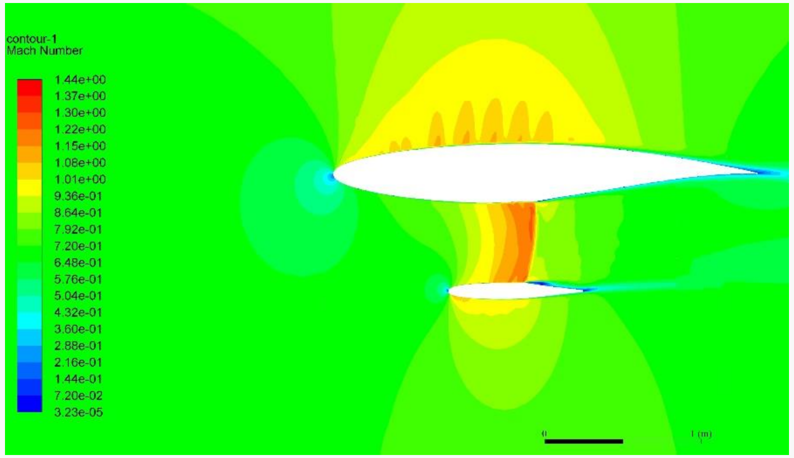
# Results

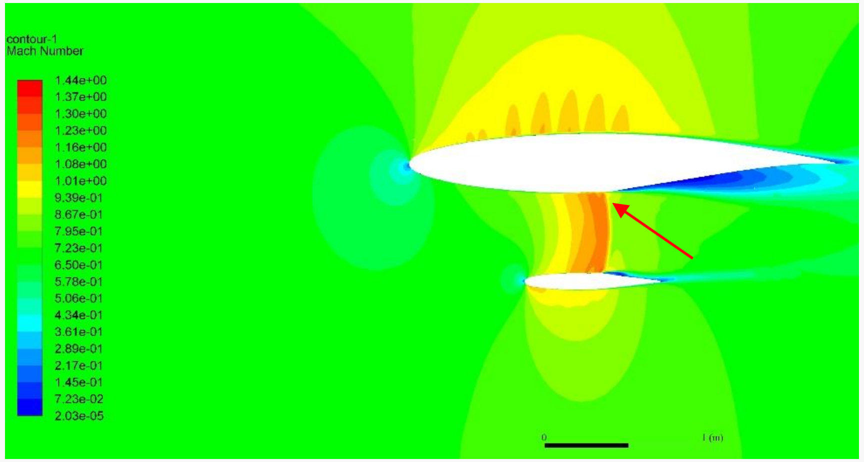
Baseline

KC-SCB_v0

KC-SCB_v2

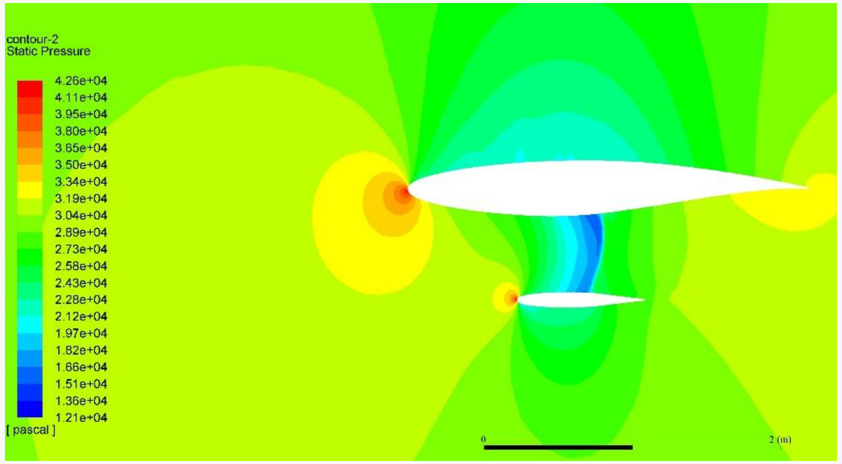


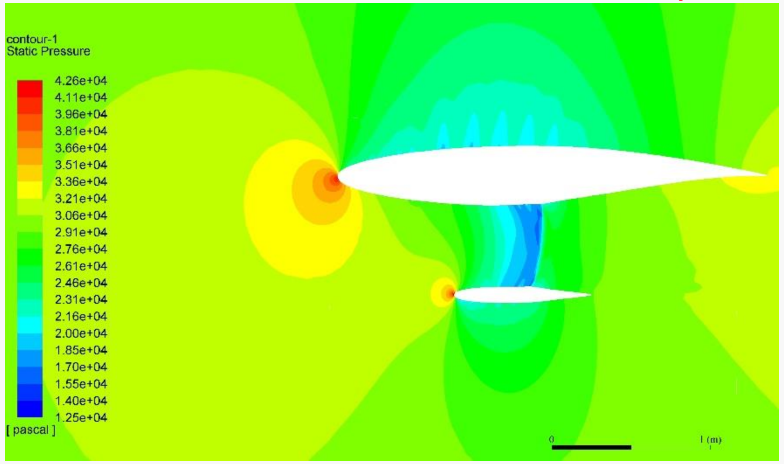



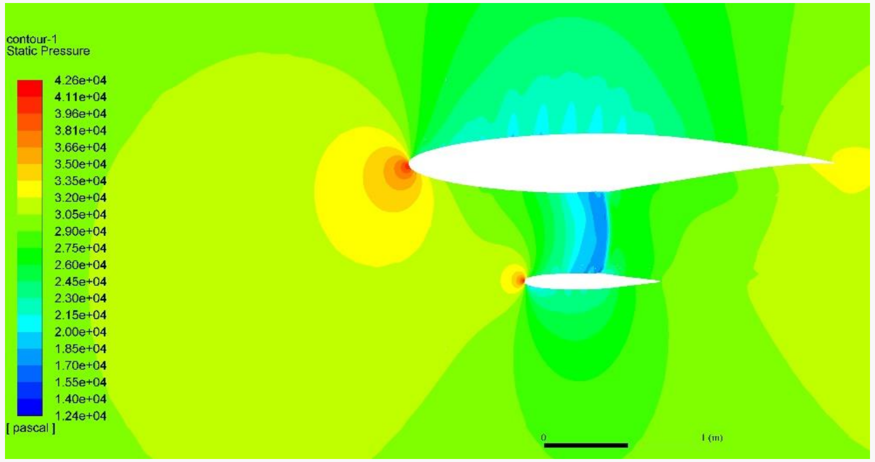




Y slice =15.5m

Separated flow



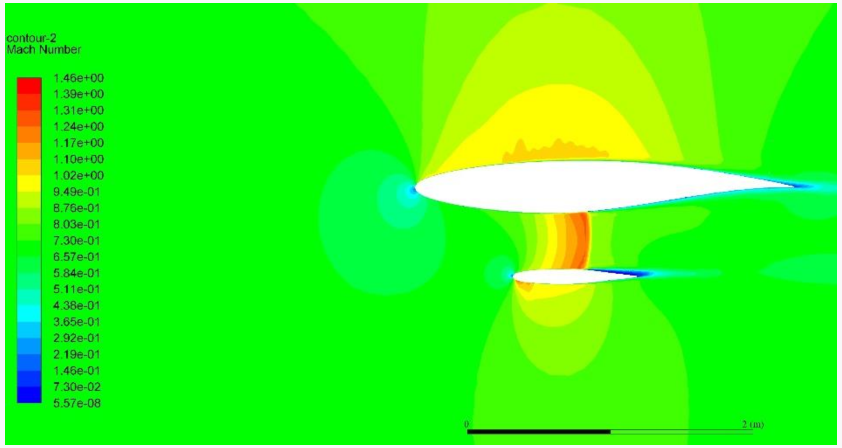



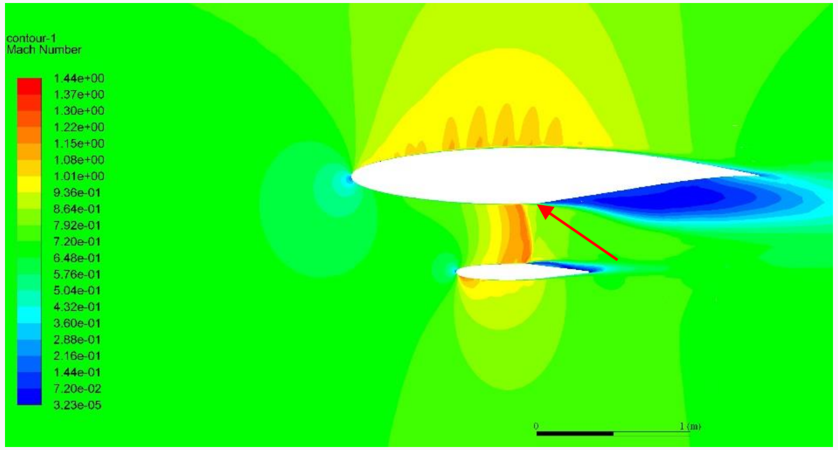



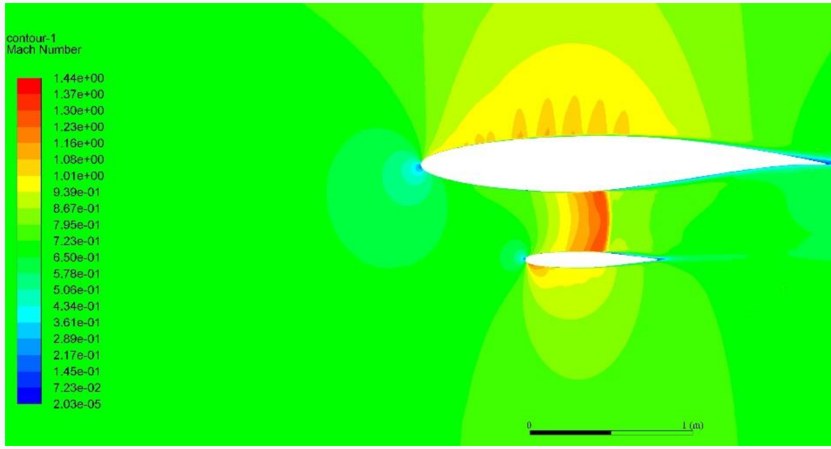
# Results

National Institute for Aerospace Research "Elie Carafoli"

Baseline | KC-SCB_v0 | KC-SCB_v2

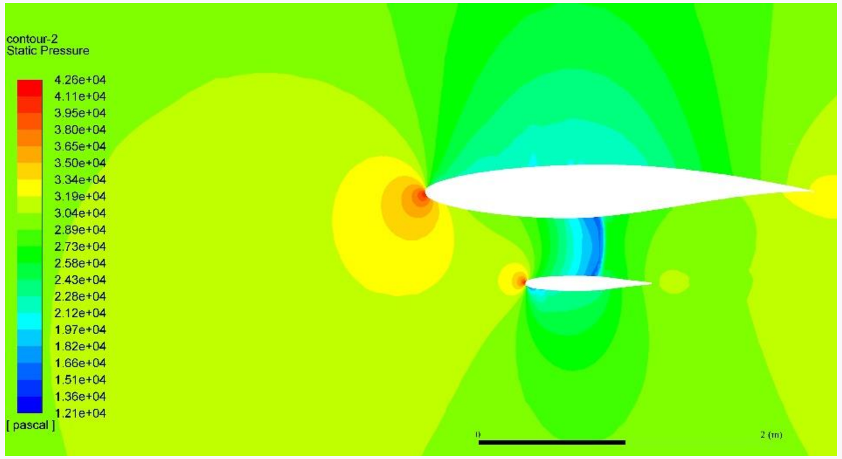


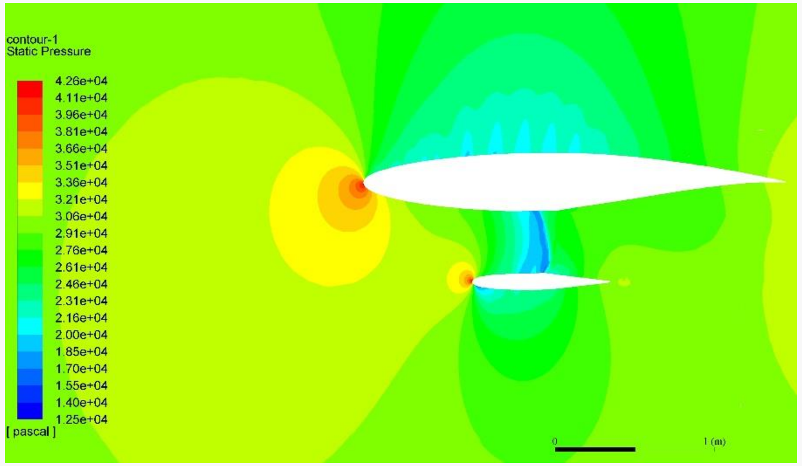



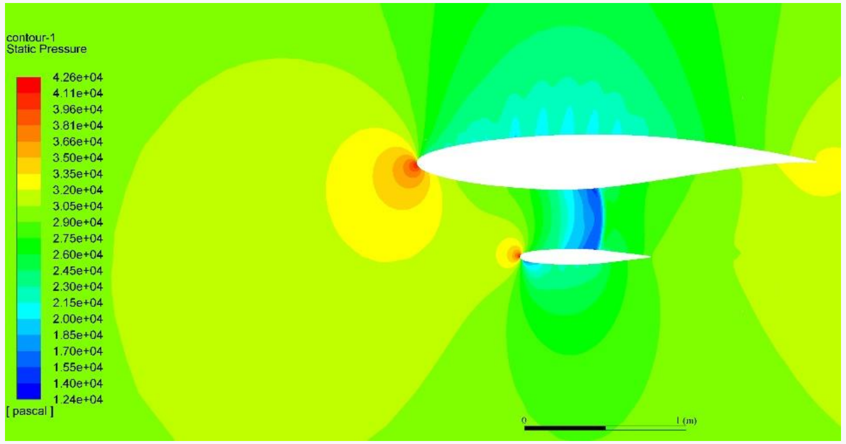




Y slice =16m

Separated flow

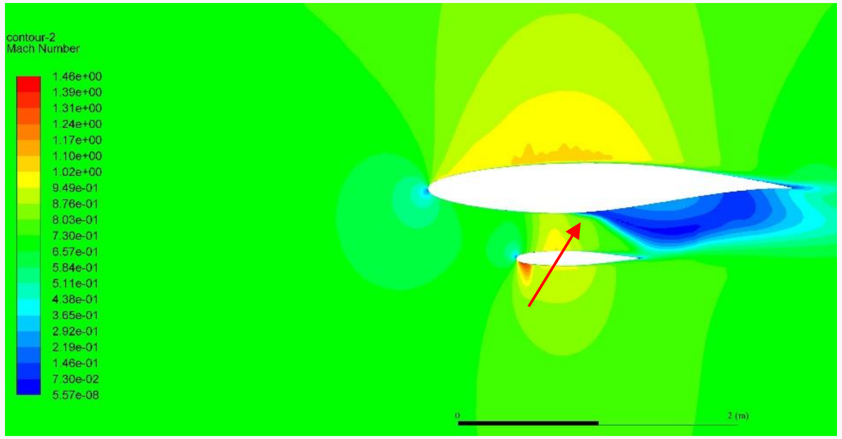


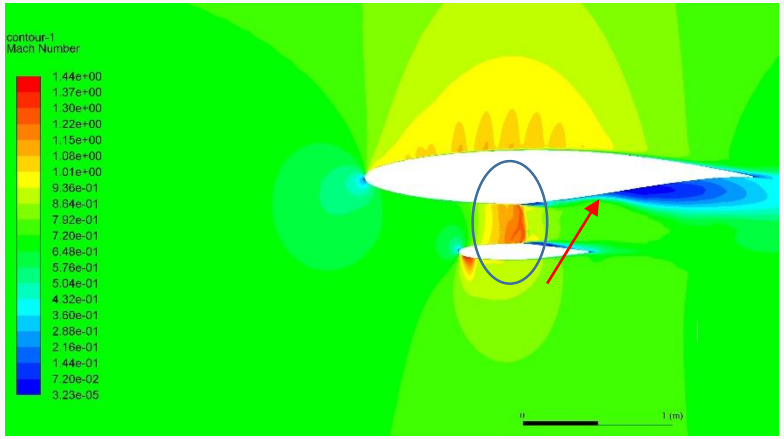



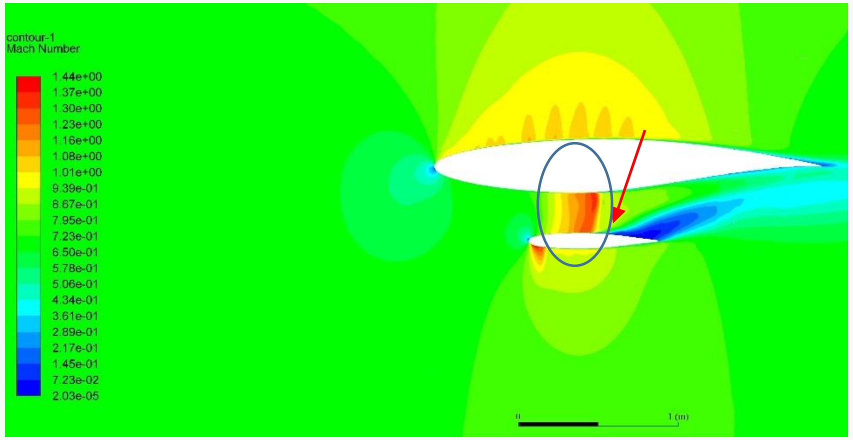



# Results

Baseline KC-SCB_v0 KC-SCB_v2

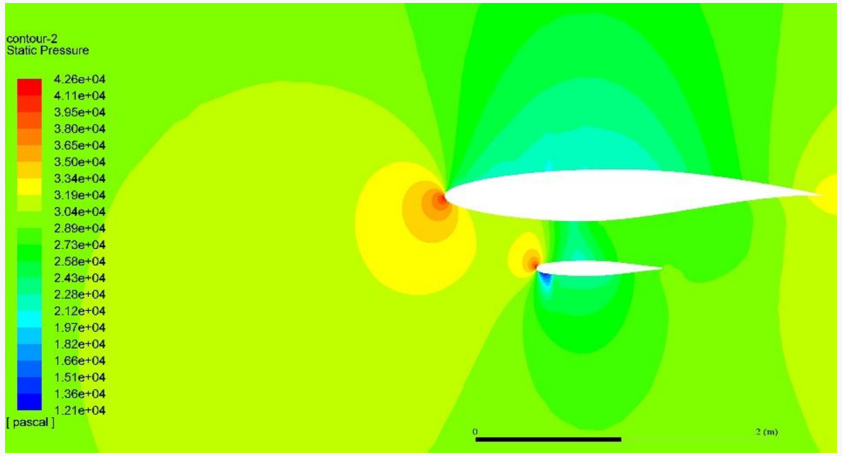


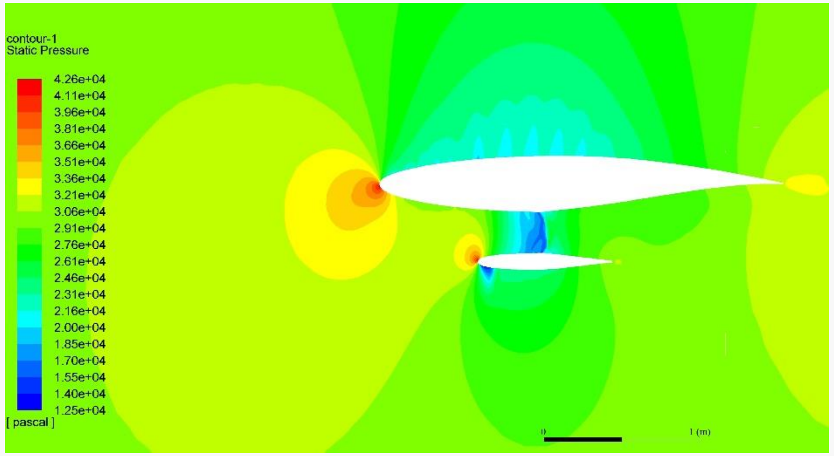



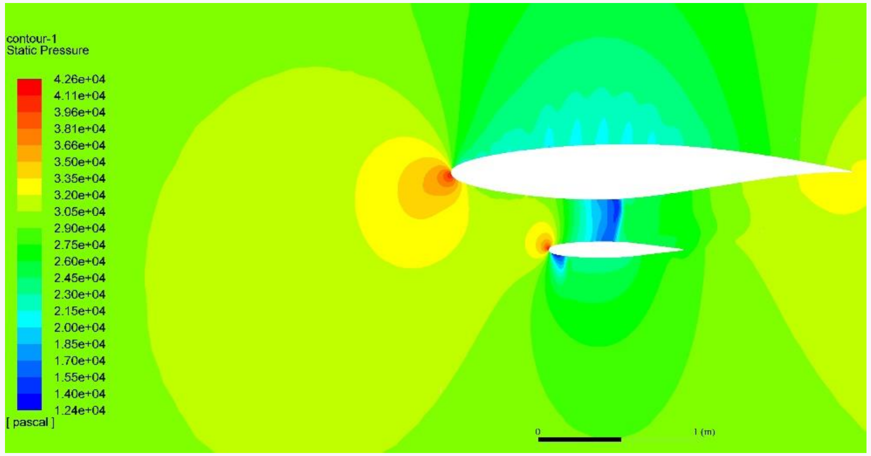




Y slice =16.5m

Separated flow and strong shock

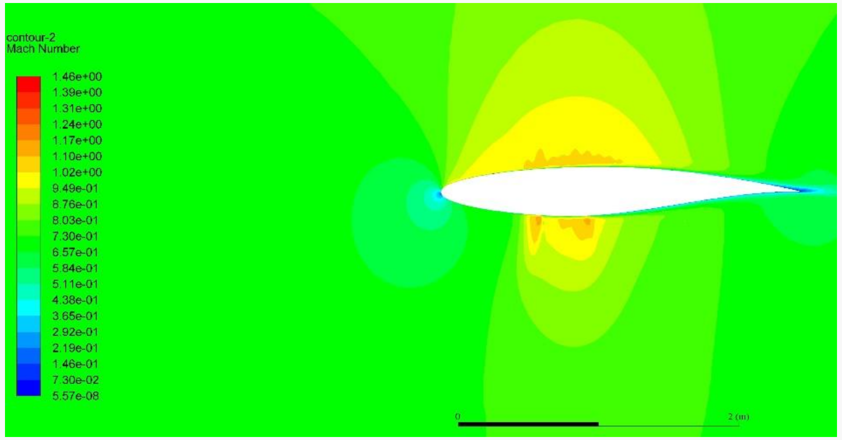


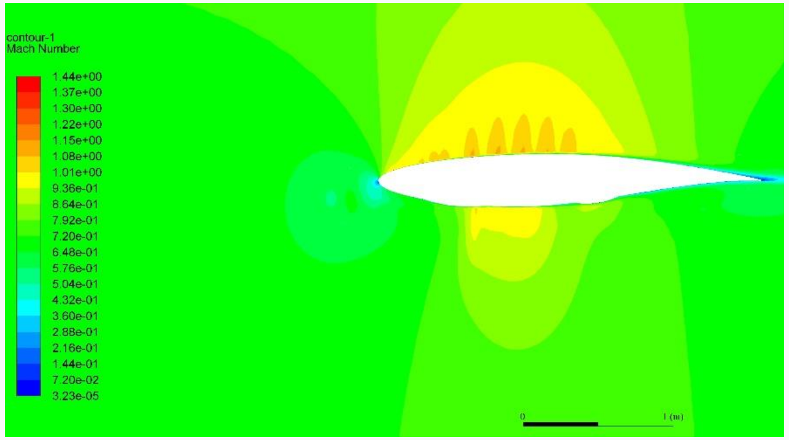



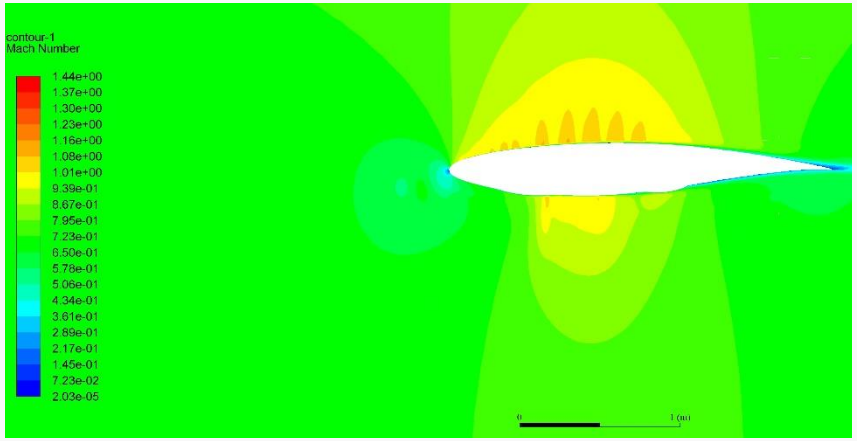



# Results

| Baseline | KC-SCB_v0 | KC-SCB_v2 |
|---|---|---|

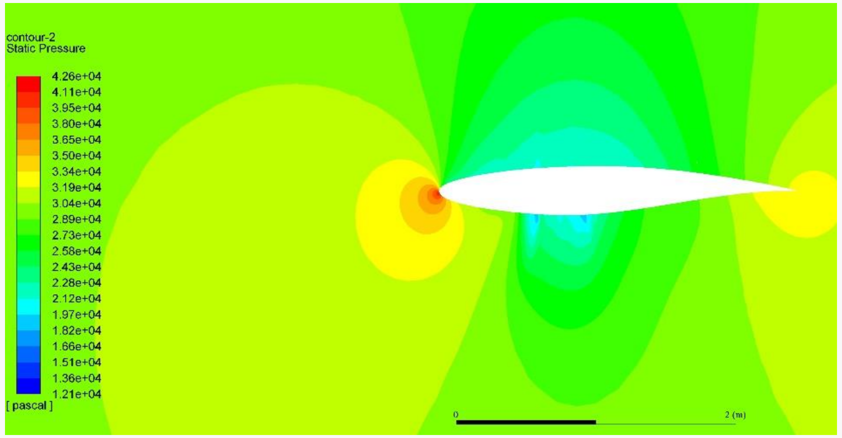


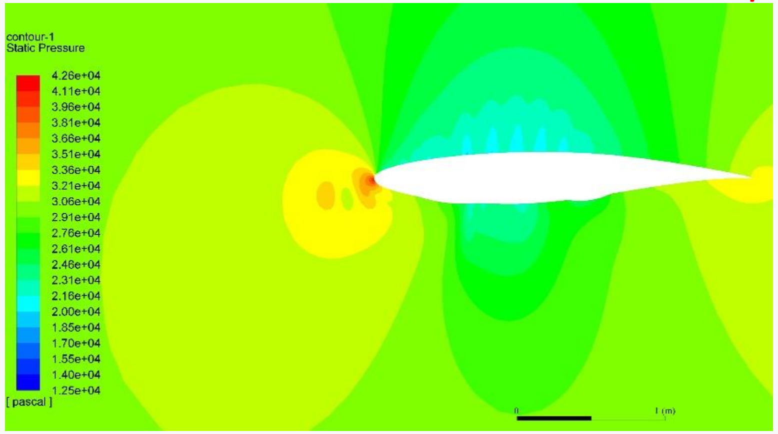



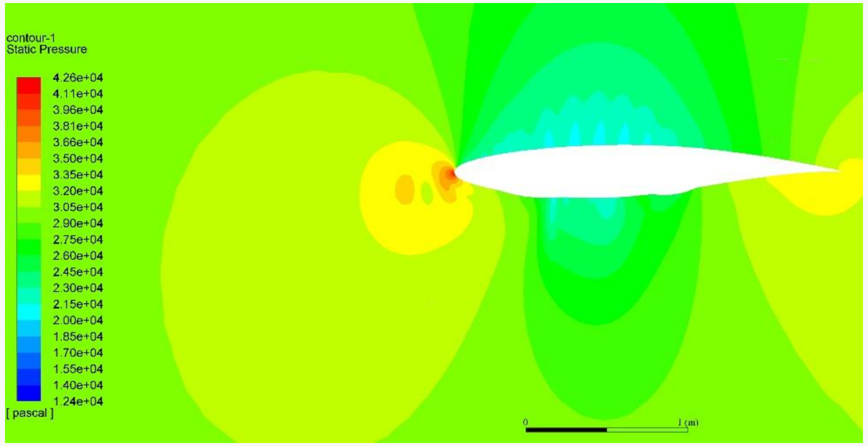




Y slice =16.8m

Little / No difference

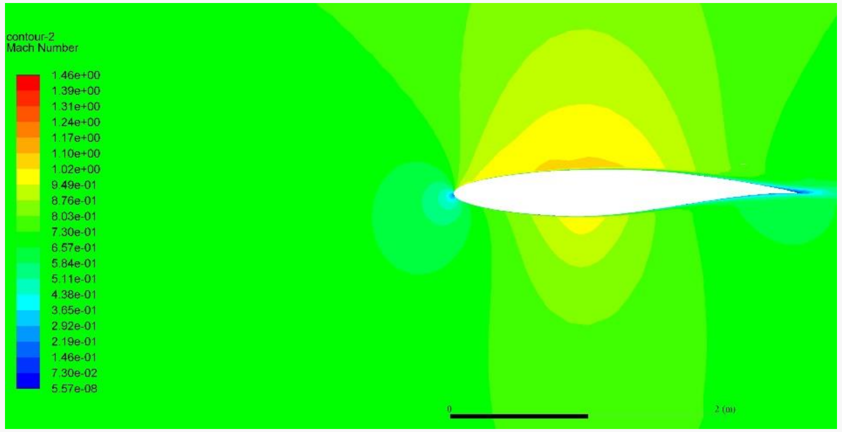


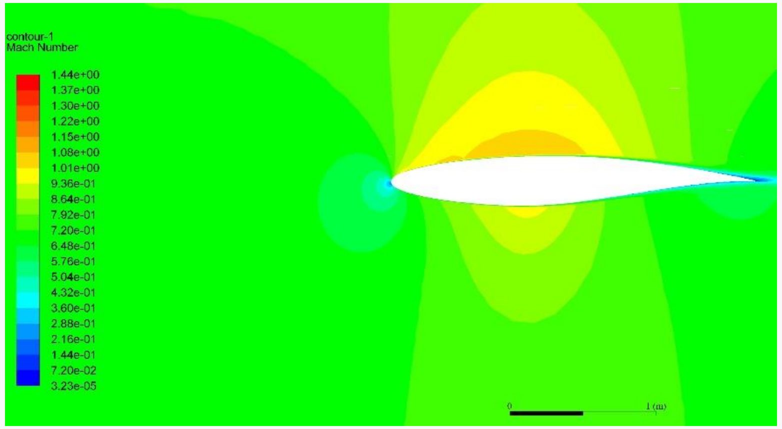



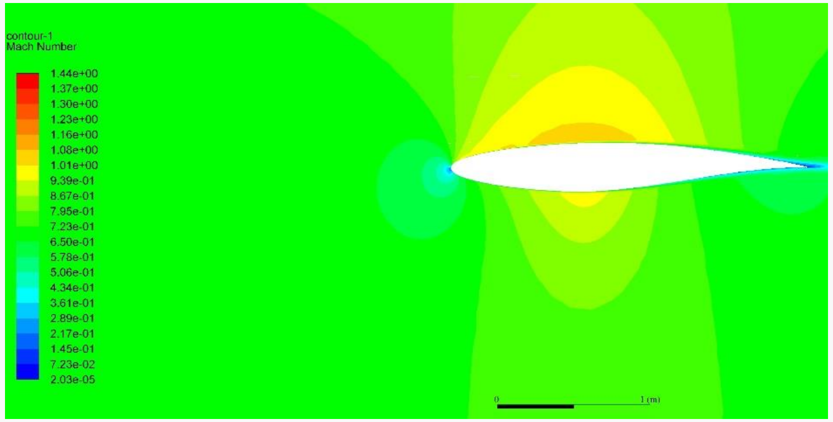



# Results

Baseline | KC-SCB_v0 | KC-SCB_v2

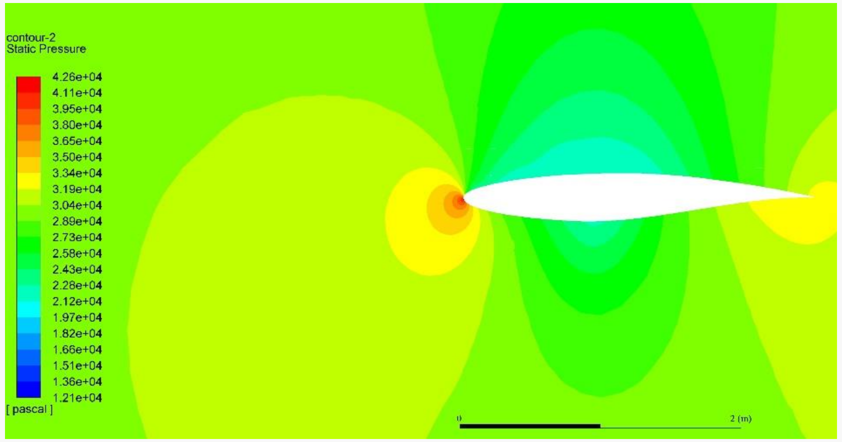


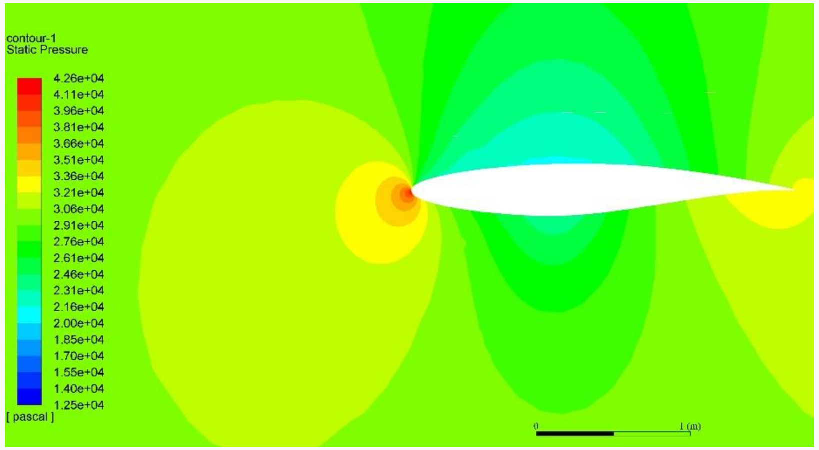



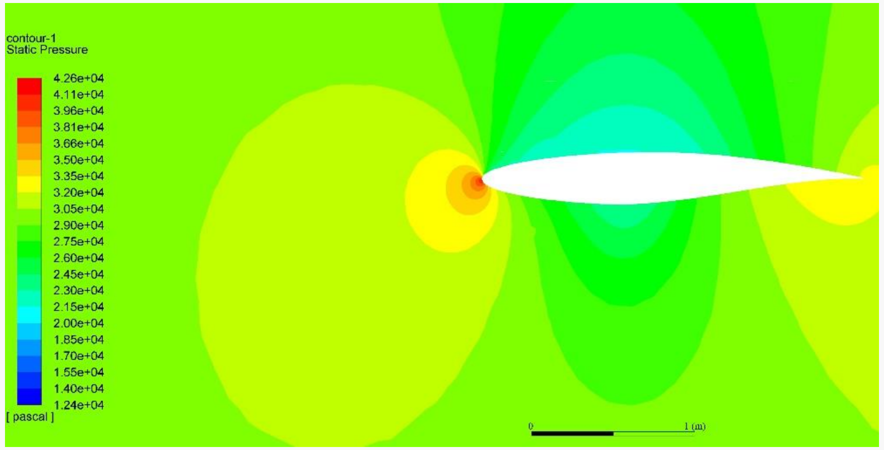




Y slice =17.3m

Little / No difference



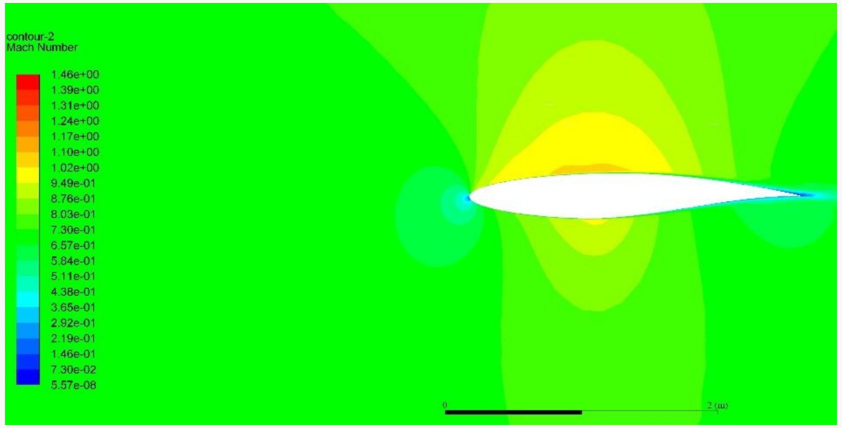



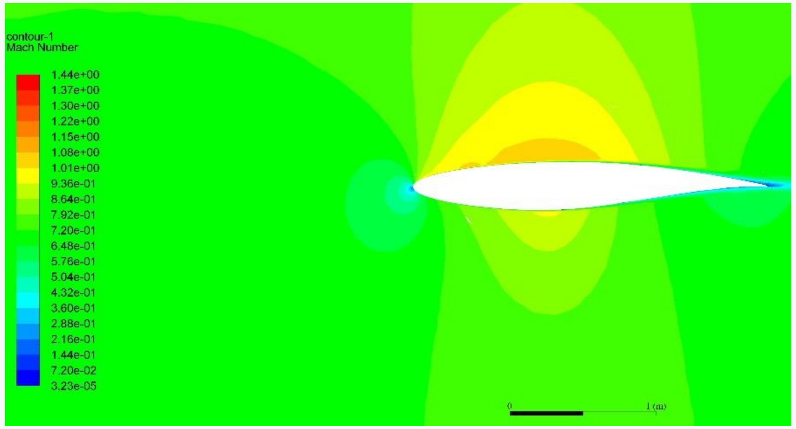



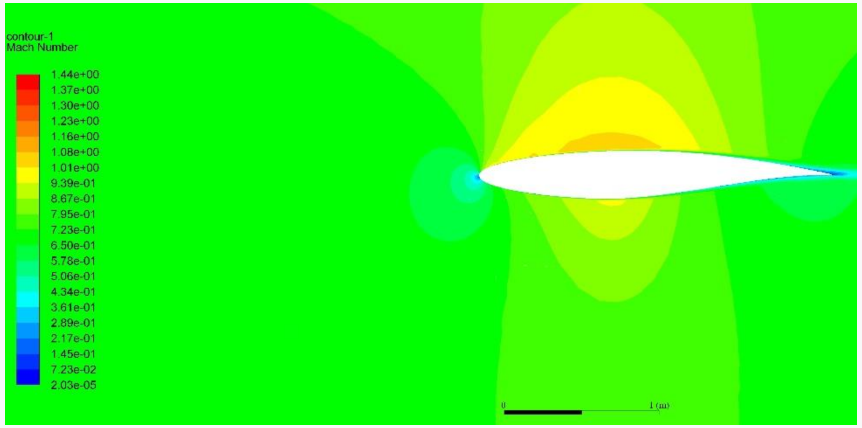
# Results



Baseline KC-SCB_v0 KC-SCB_v2

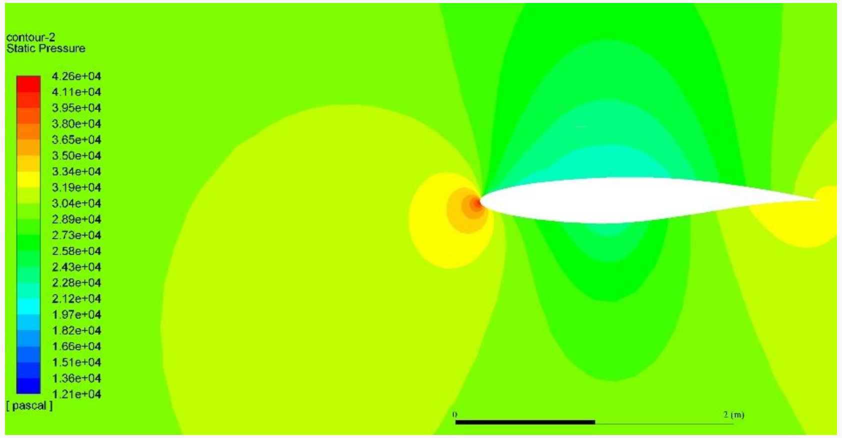


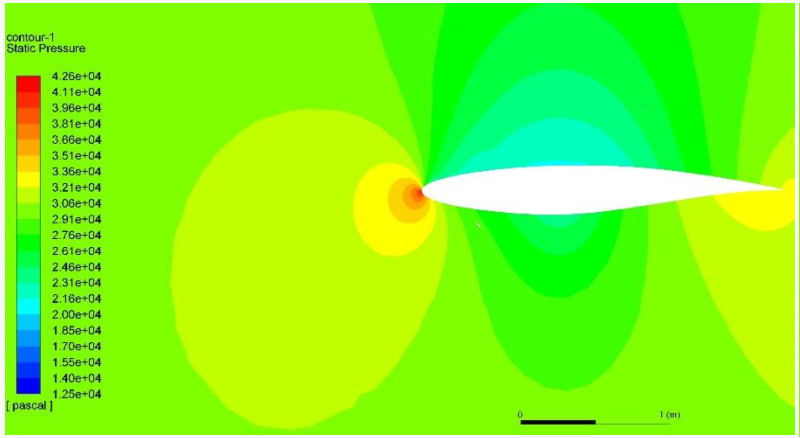



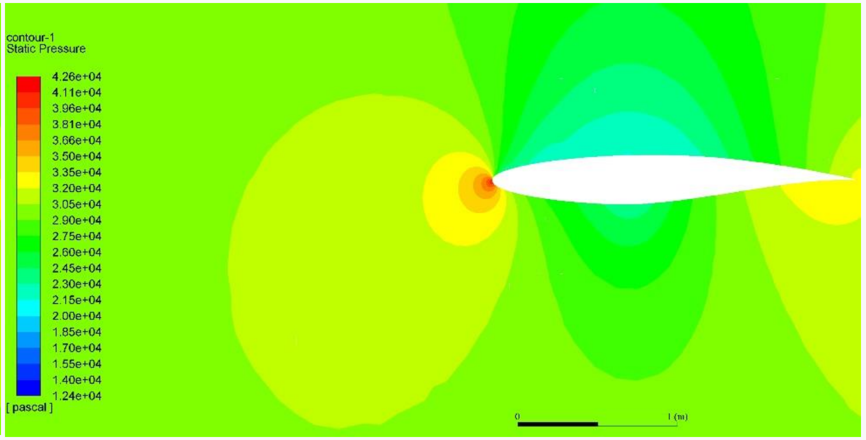




Y slice =17.8m

Little / No difference



# Results

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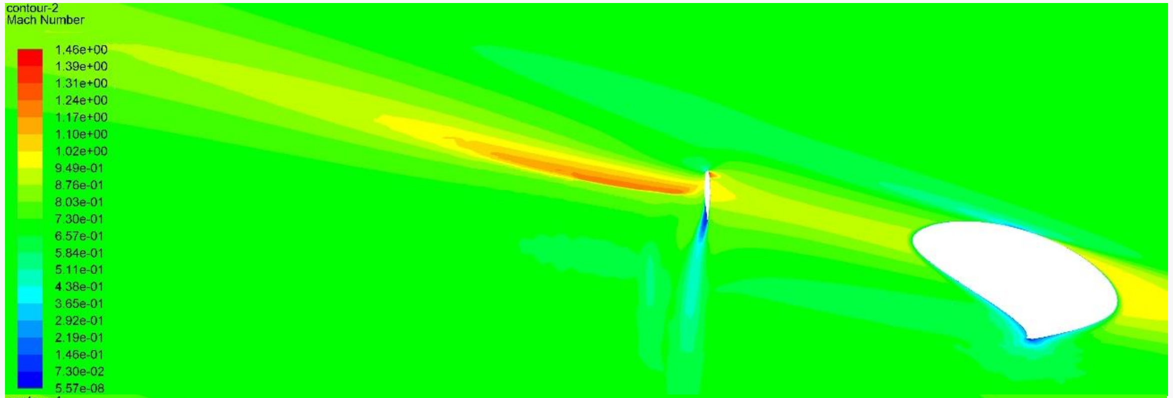
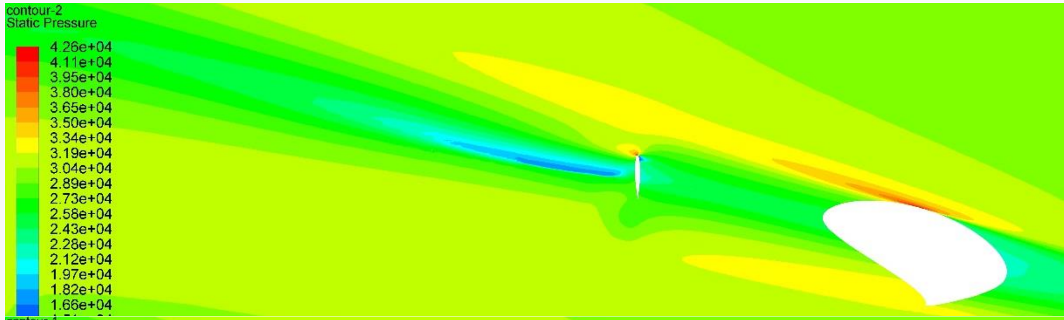
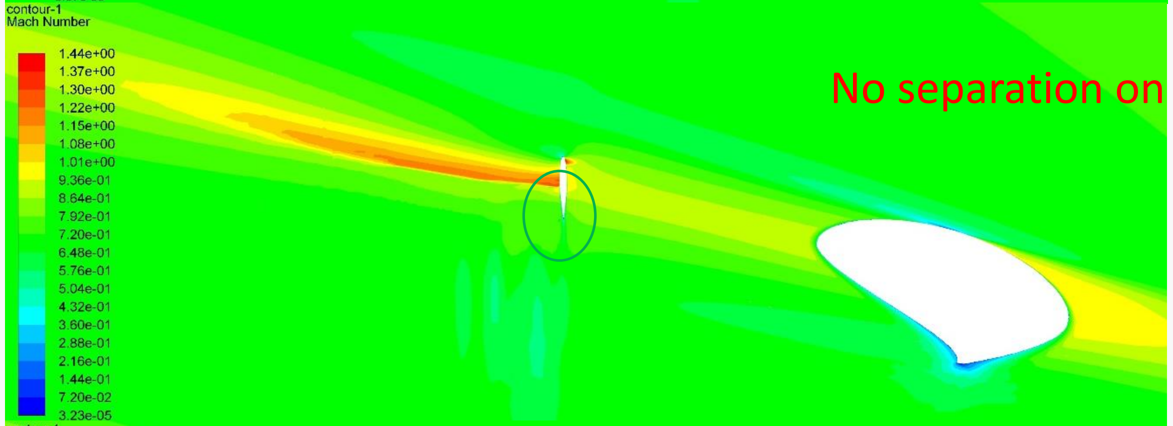
Z slice =0.87m

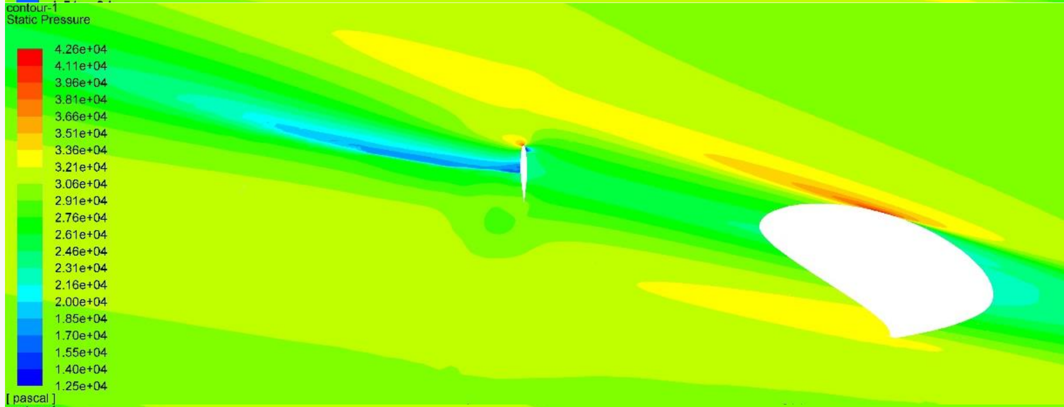


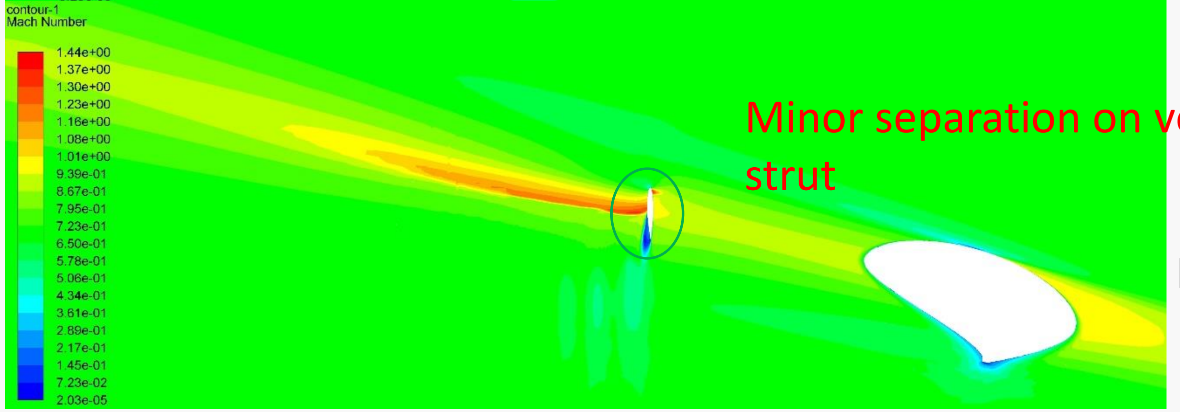

Baseline



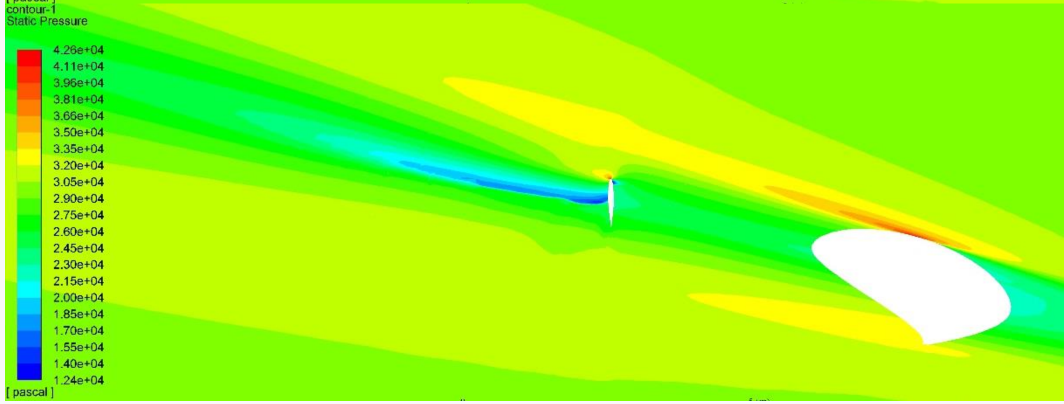

No separation on vertical strut




KC-SCB_v0



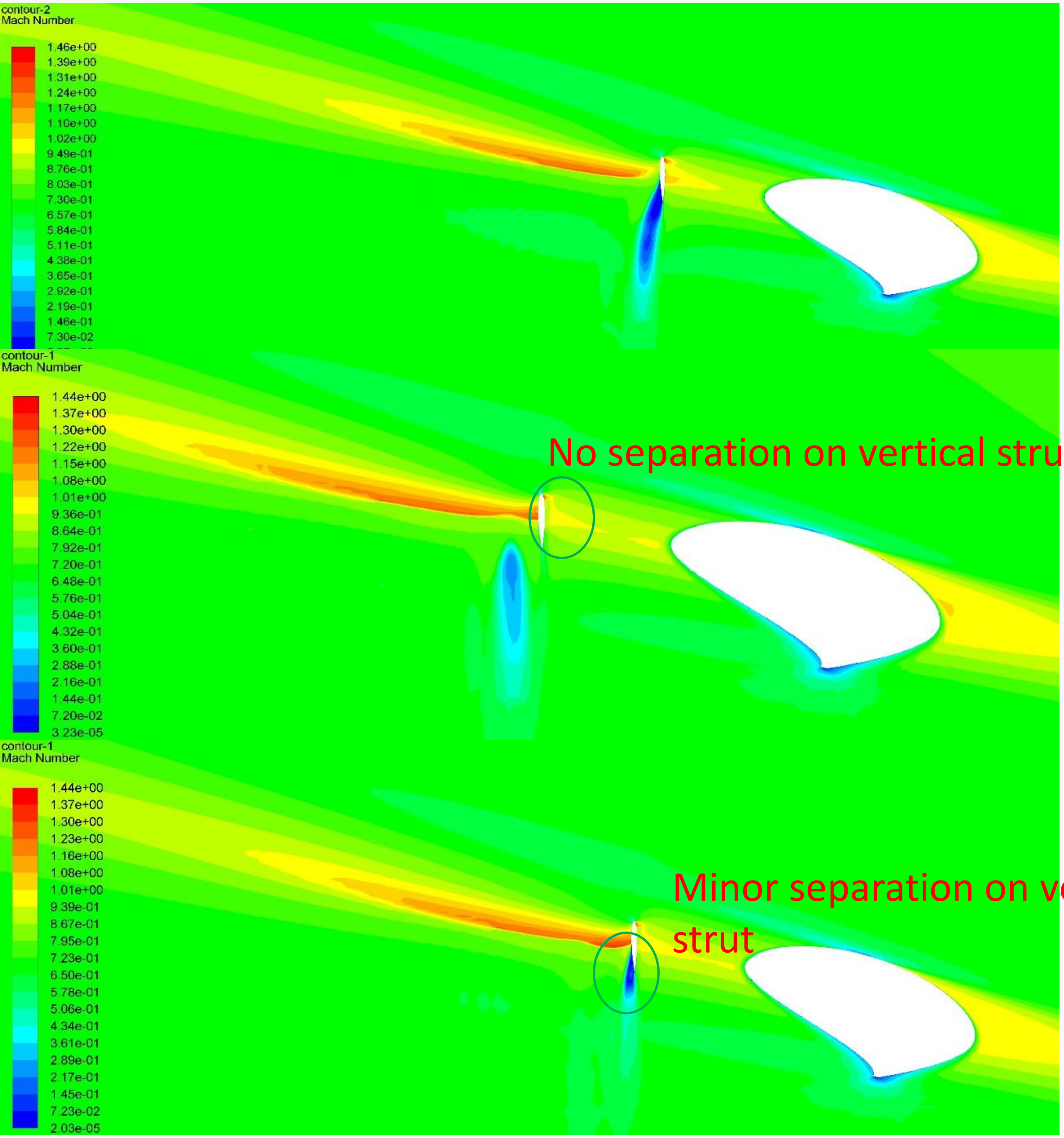

Minor separation on vertical strut




KC-SCB_v2

# Results

Z slice =0.97m



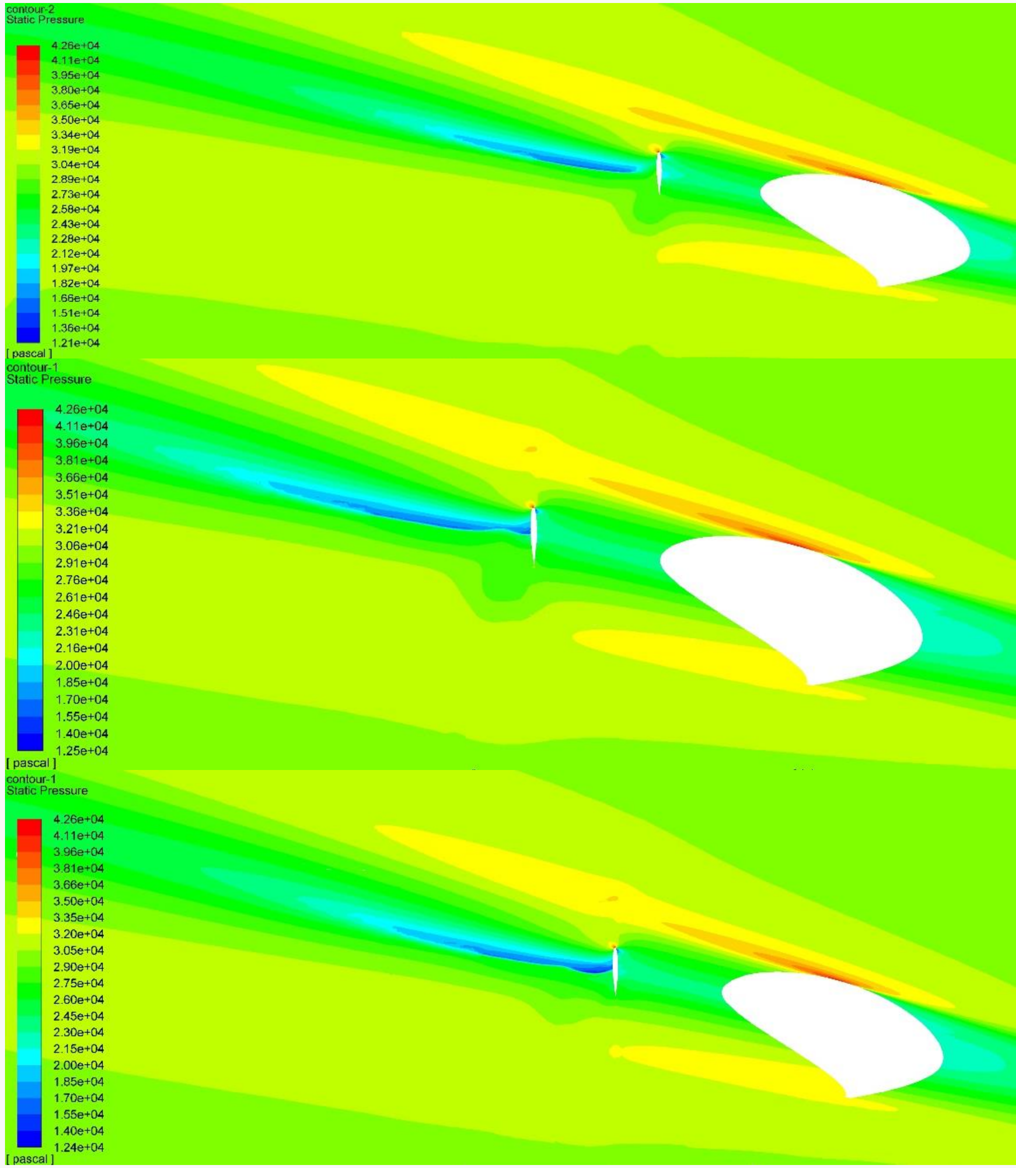

Baseline

No separation on vertical strut, but on the wing

KC-SCB_v0

Minor separation on vertical strut

KC-SCB_v2

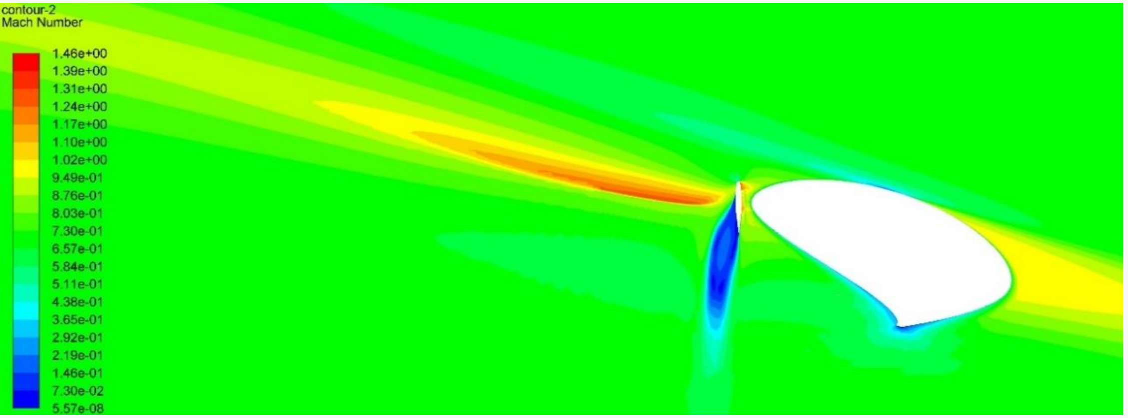


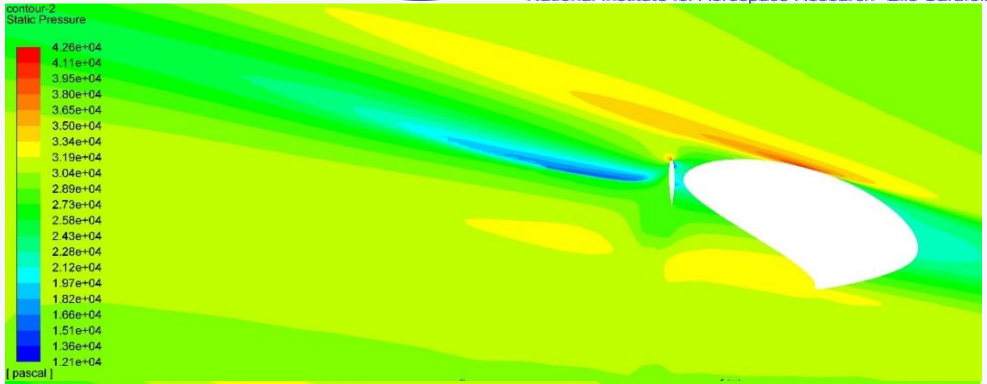
# Results

National Institute for Aerospace Research "Elie Carafoli"

Z slice =1.07m

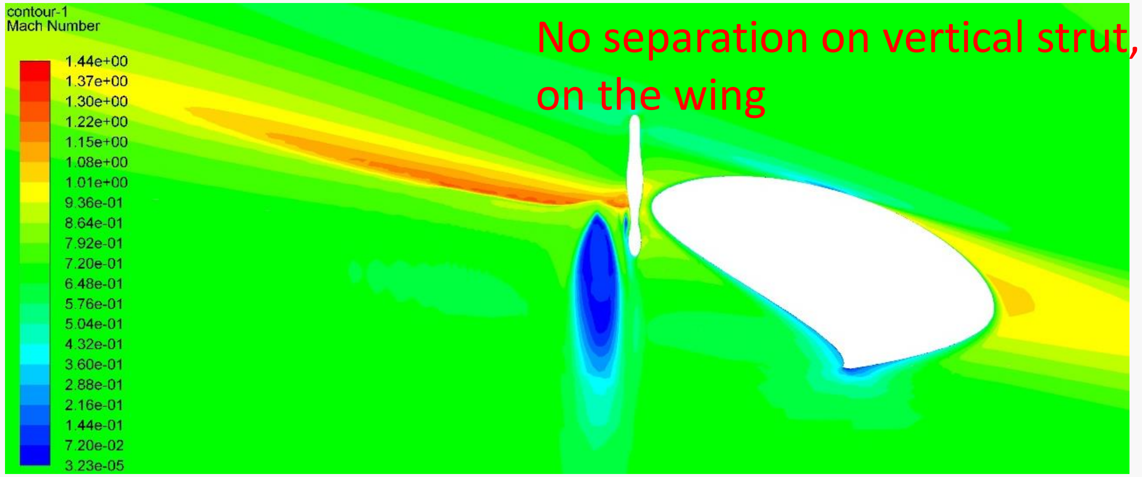
Baseline

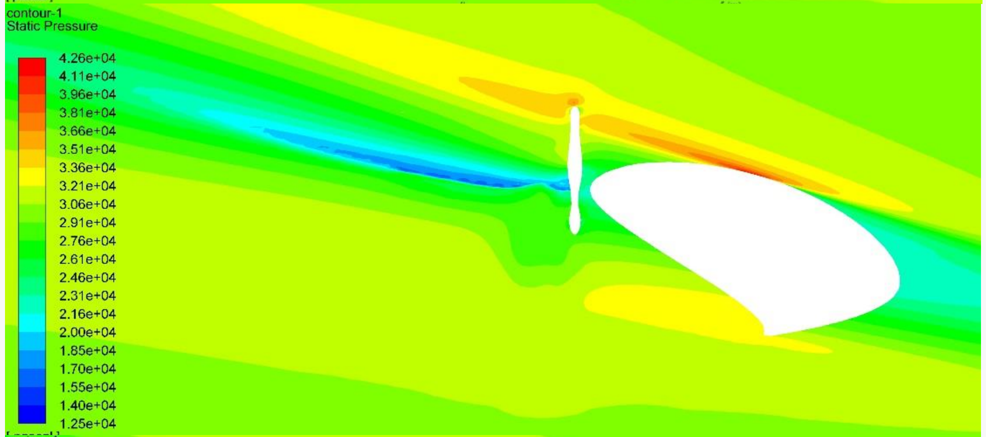



KC-SCB_v0

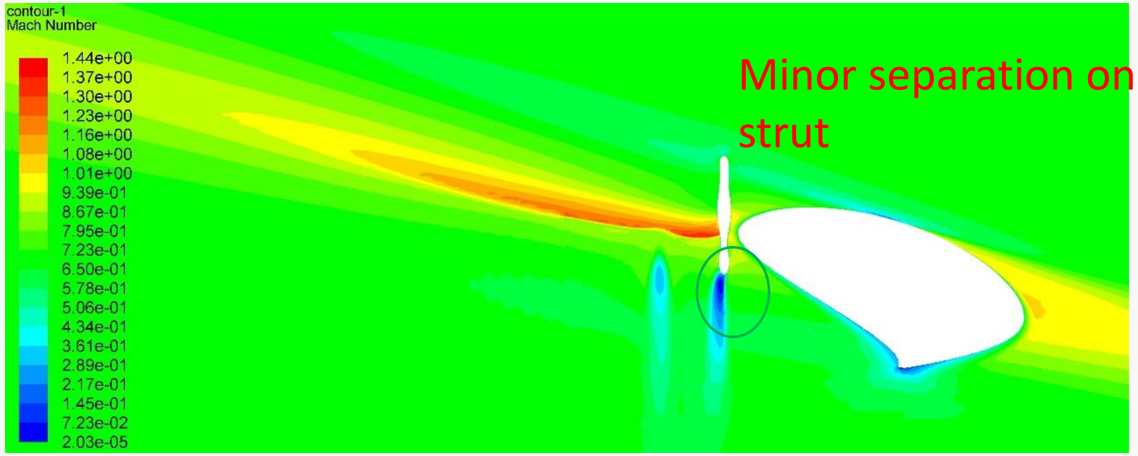
No separation on vertical strut, but massively on the wing

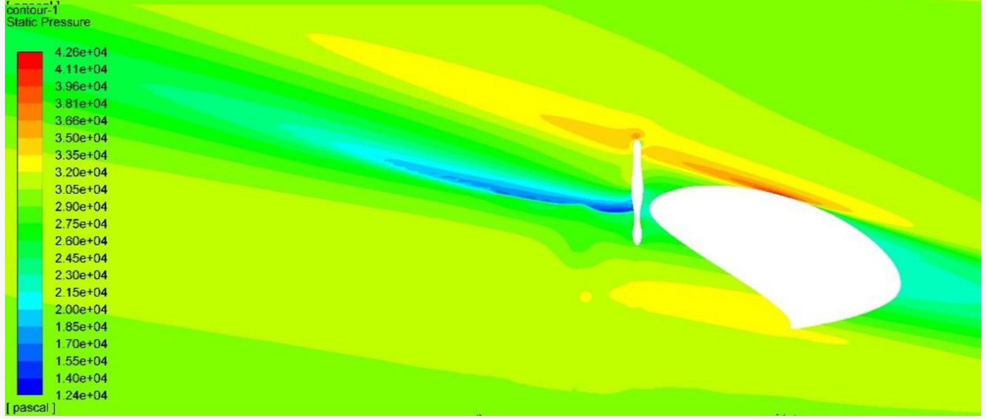



KC-SCB_v2

Minor separation on vertical strut



# Conclusions

National Institute for Aerospace Research "Elie Carafoli"

KC :

- Mitigates drag by locally controlling the flow at the wing strut junction
- Reduces flow separation on the wing, but induces on the strut--- to be improved!
- Improves flow also on the outer wing panel
- KC to be numerically optimized !

SCB :

- Mitigates drag by globally/span-wise controlling the flow
- To be verified a staggered arrangement on the wing/strut, or other formations
- SCBs to be numerically optimized in shape and orientation w.r.t. local flow direction!

KC-SCB:

- More work required, but there is “hope”!
- The trend is clear to reduce drag, just by “manually” improving the SCB number and position
- To be verified a staggered arrangement on the wing/strut, or other formations (?)
- SCBs to be numerically optimized in shape and orientation w.r.t. local flow direction!
- SCB close to the KC are aligned with the ideal flow direction not the local/KC induced one!

Thank you !

Questions ?