PHYSICS OF SPANWISE GAPS BETWEEN LIFTING AND CONTROL SURFACES: AN ANALYSIS USING RANS AND HYBRID RANS-LES METHODS

24. DGLR STAB-SYMPOSIUM

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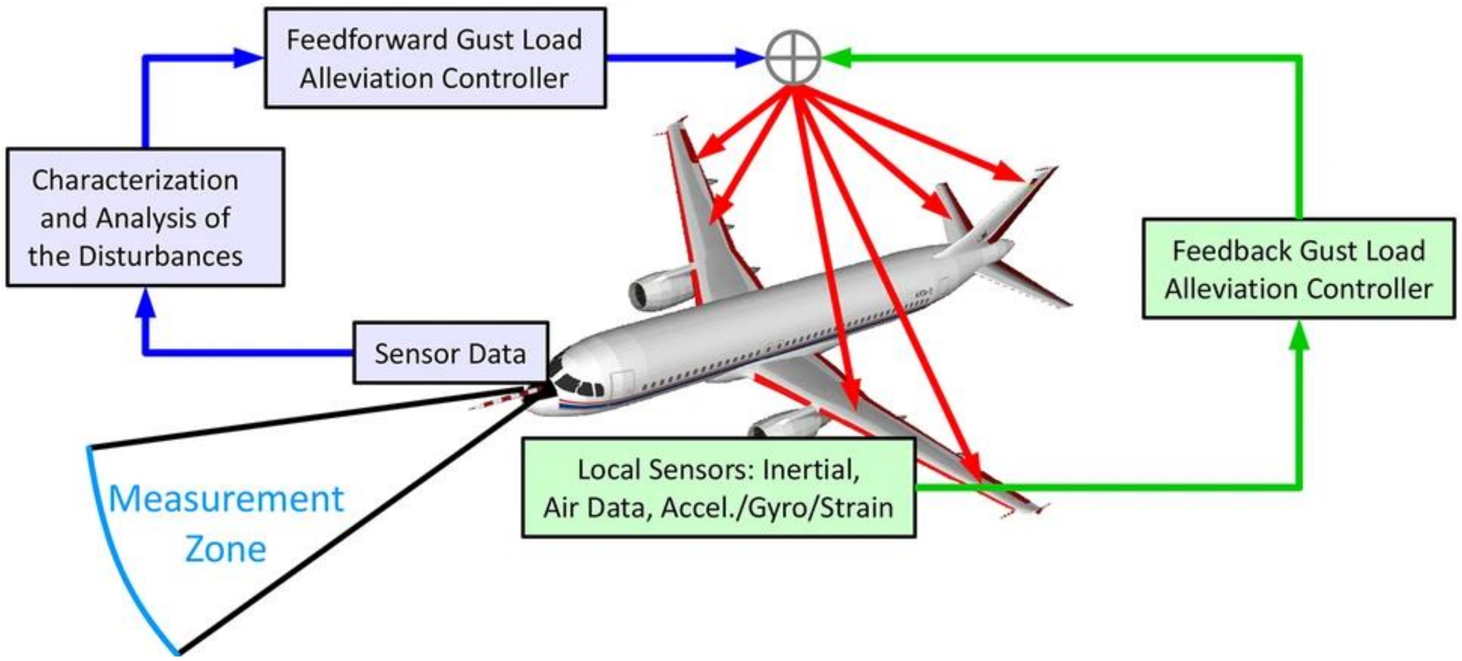
DLR

Regensburg, 14.11.2024

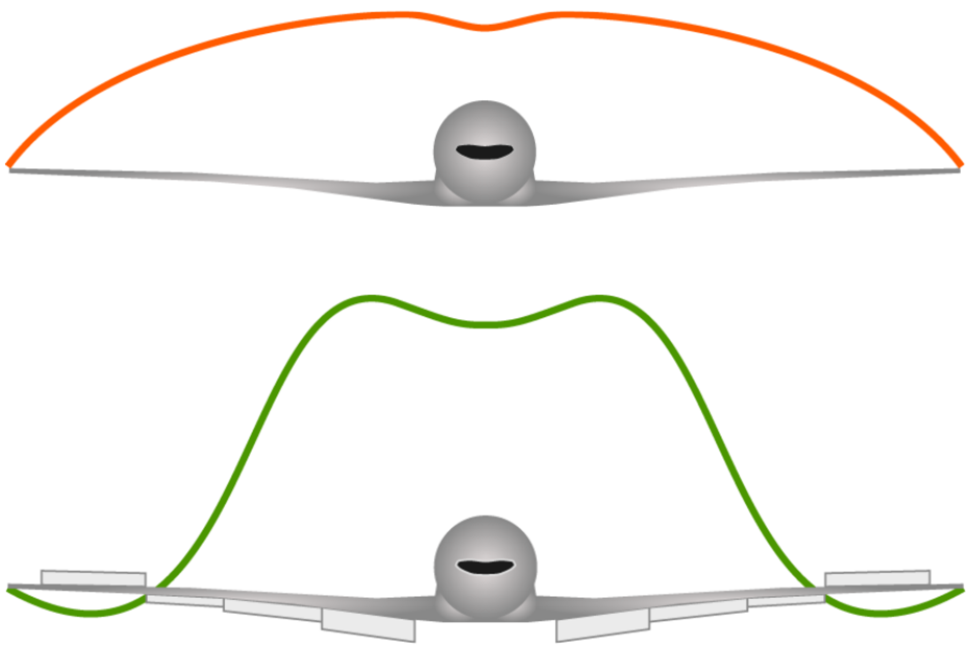
Motivation

- Design more efficient aircraft
  - Active control systems

Gust load alleviation system [1]



Maneuver load alleviation system [2]

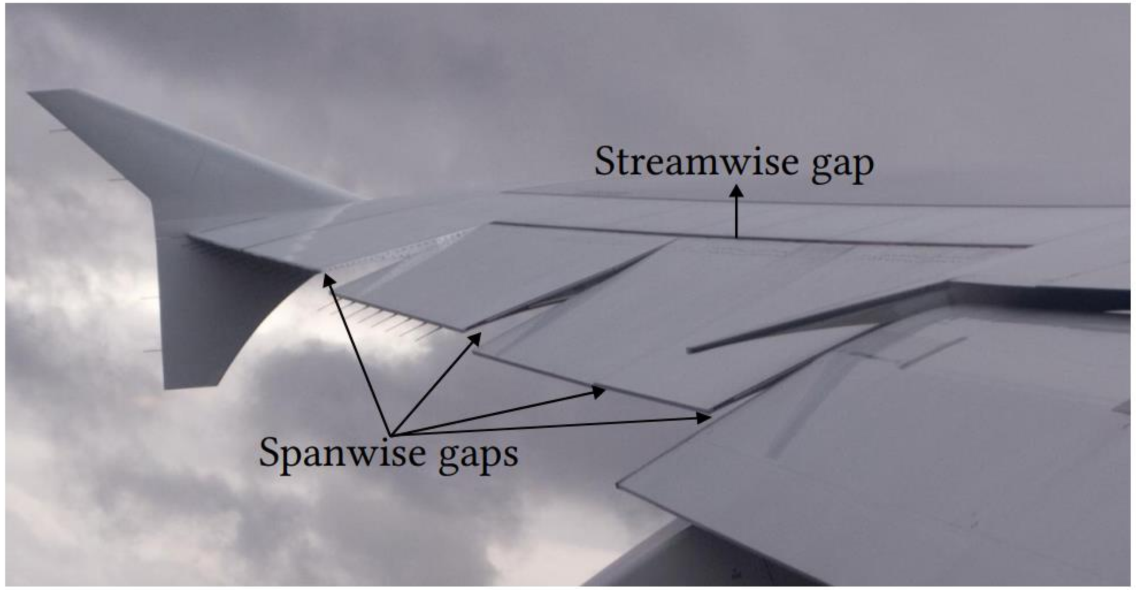


[1] Fezans, N., Joos, HD. & Deiler, C. (2019). Gust load alleviation for a long-range aircraft with and without anticipation. *CEAS Aeronaut J* **10**, 1033–1057.

[2] Xu, J. and Kroo, I. (2014). Aircraft design with active load alleviation and natural laminar flow. *Journal of Aircraft* **51**(5), 1532-1545.

Motivaton

- Design more efficient aircraft
  - Active control systems
    - High-fidelity modeling of control surfaces



Airbus A380 [3].

Aileron seal of the LS8 glider [4].

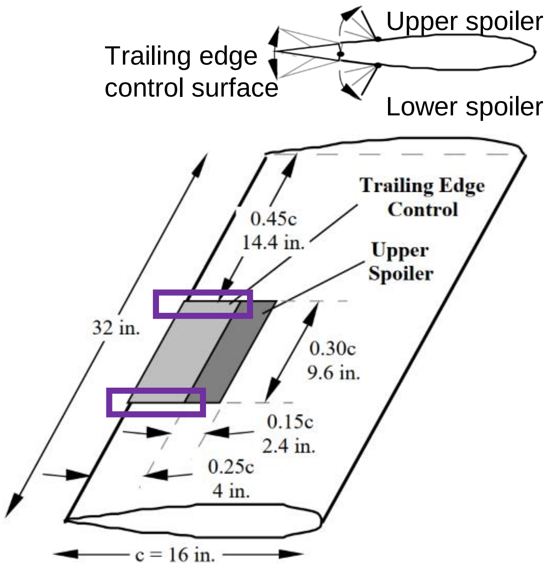
[3] Aviation Stack Exchange (2018). Why do some aircraft have multiple ailerons per wing? https://aviation.stackexchange.com/questions/921/why-do-some-aircraft-havemultiple-ailerons-per-wing. Accessed: 30.03.2024.

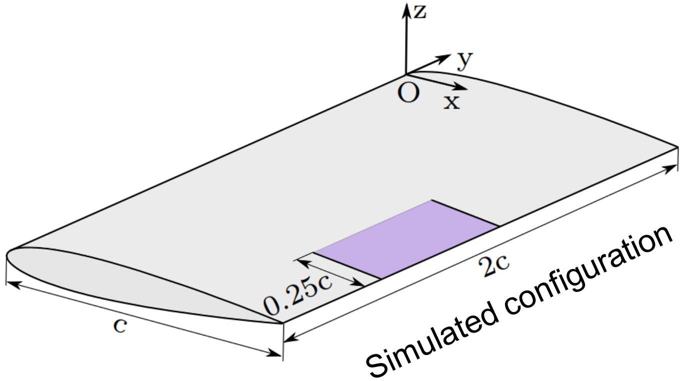
[4] Navboys (2024). LS8 aileron seal bundle. https://www.navboys.com/ls8-aileron-sealbundle.html. Accessed: 30.03.2024.

Test case
Benchmark Active Control Technology (BACT) configuration

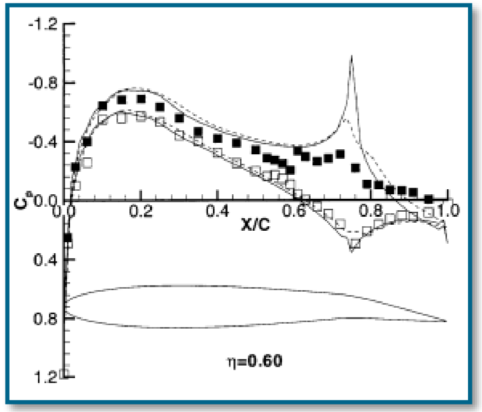
- BACT configuration
  - NACA0012 wing
  - Trailing edge control surface + spanwise gaps + streamwise gap
  - Upper and lower spoilers + cavities
- Experimental results from NASA
  - Various flow conditions (subsonic to transonic)
  - Various control surface deployment angles
  - Statically deployed control surface
  - Harmonically oscillating control surface
  - NO measurements on the spanwise gaps

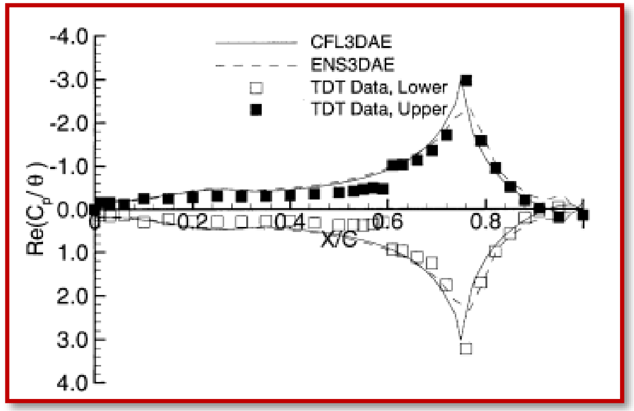
Original configuration

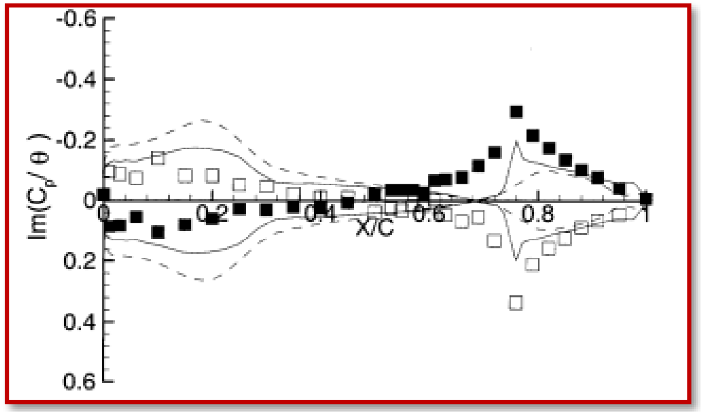




Simulated configuration



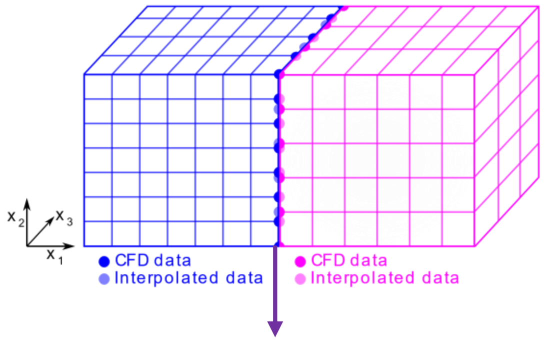


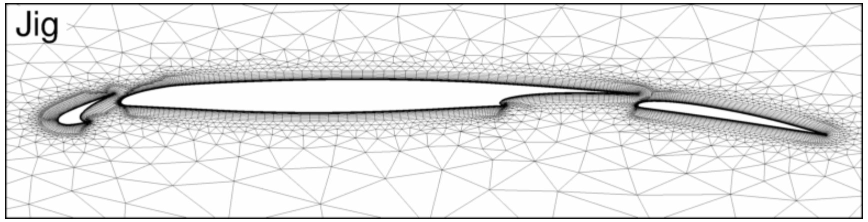


BACT test case
Control surface modeling

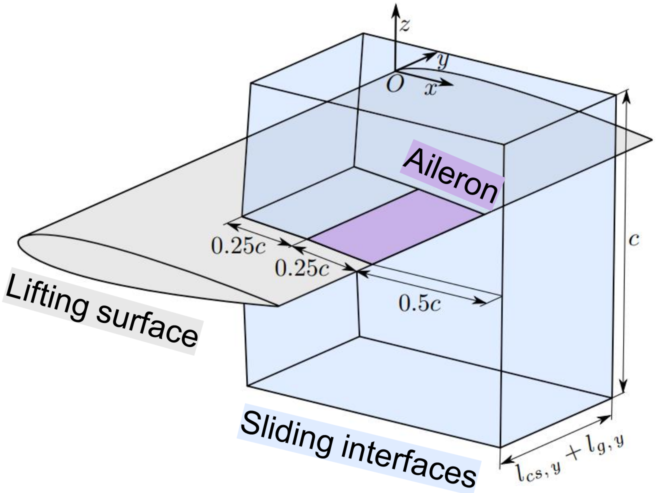
- Combination of mesh deformation with sliding interfaces

Sliding interfaces + RBF mesh deformation

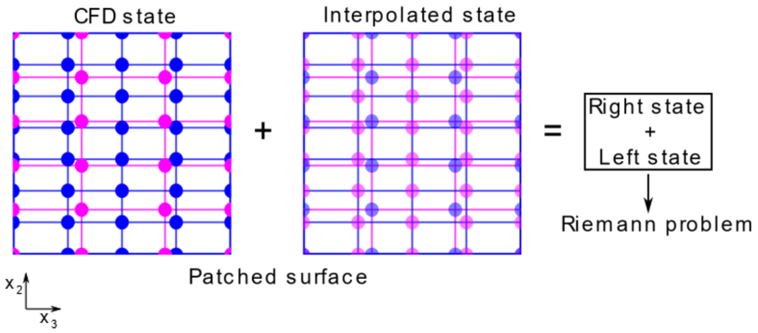




*exemplary figure of how RBF works



Convective fluxes + Viscous and turbulent fluxes



Averaged state

$$u_{i,\,avg} = \frac{u_{i,\,CFD} + u_{i,\,interp}}{2}$$

$$\left.\frac{\partial u}{\partial x}\right|_{i,\,avg} = \frac{\left.\frac{\partial u}{\partial x}\right|_{i,\,CFD} + \left.\frac{\partial u}{\partial x}\right|_{i,\,interp}}{2}$$

+

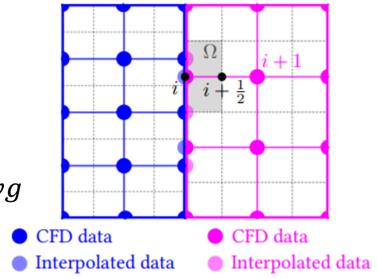
Adapted Green-Gauß gradient

$$\frac{\delta u}{\delta x_j} = \frac{1}{\Omega}\sum_{i=1}^{N_f} u_i\,\vec{n}_i \Delta S_i$$

For volume Ω

$$u_i = \frac{1}{2}\left(u_{i,\,CFD} + u_{i,\,interp}\right) = u_{avg}$$

$$u_{i+1/2} = \frac{1}{2}\left(u_{i,\,CFD} + u_{i+1,\,CFD}\right)$$



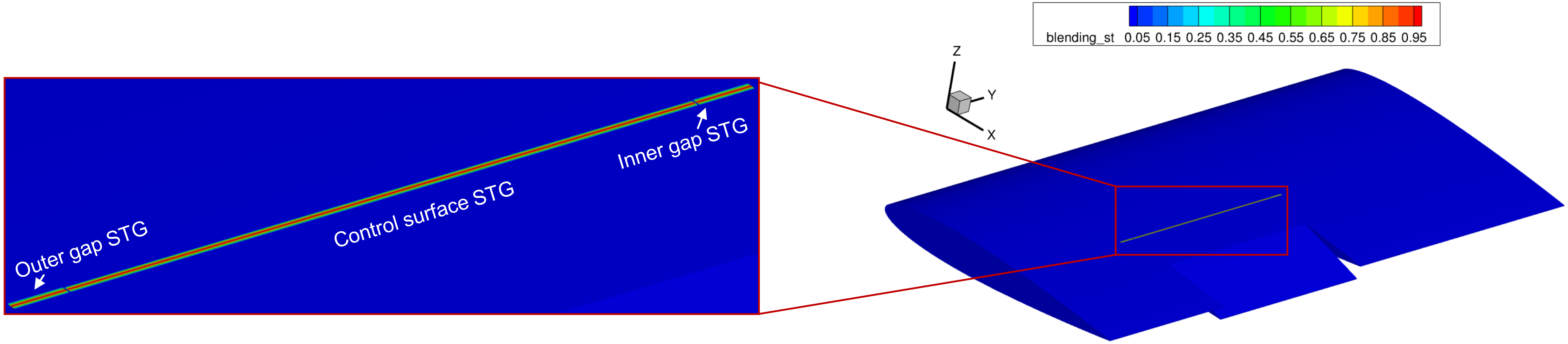
BACT test case
Turbulence modeling

RANS

- Turbulence models
  - Spalart-Allmaras model in the negative form (SA RANS)
  - Shear stress transport model in the K-g form (SST RANS)

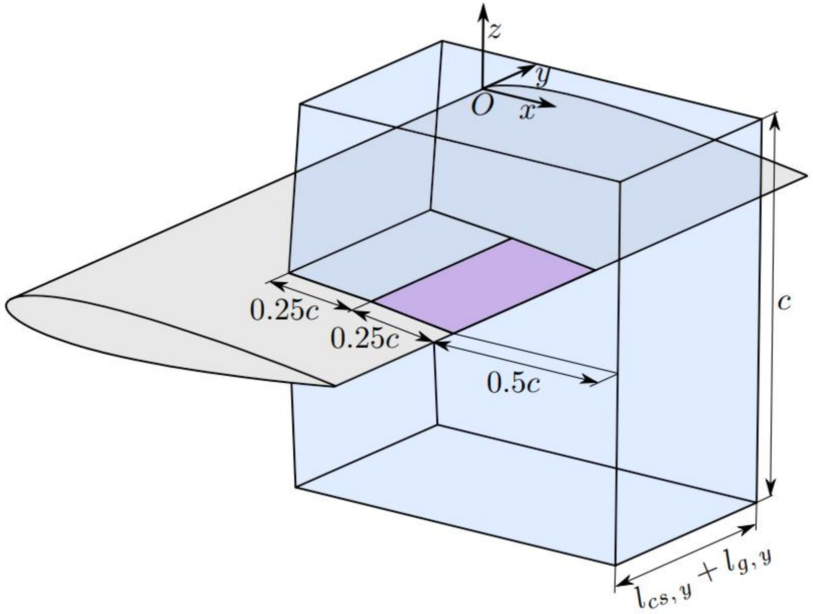
Hybrid RANS-LES

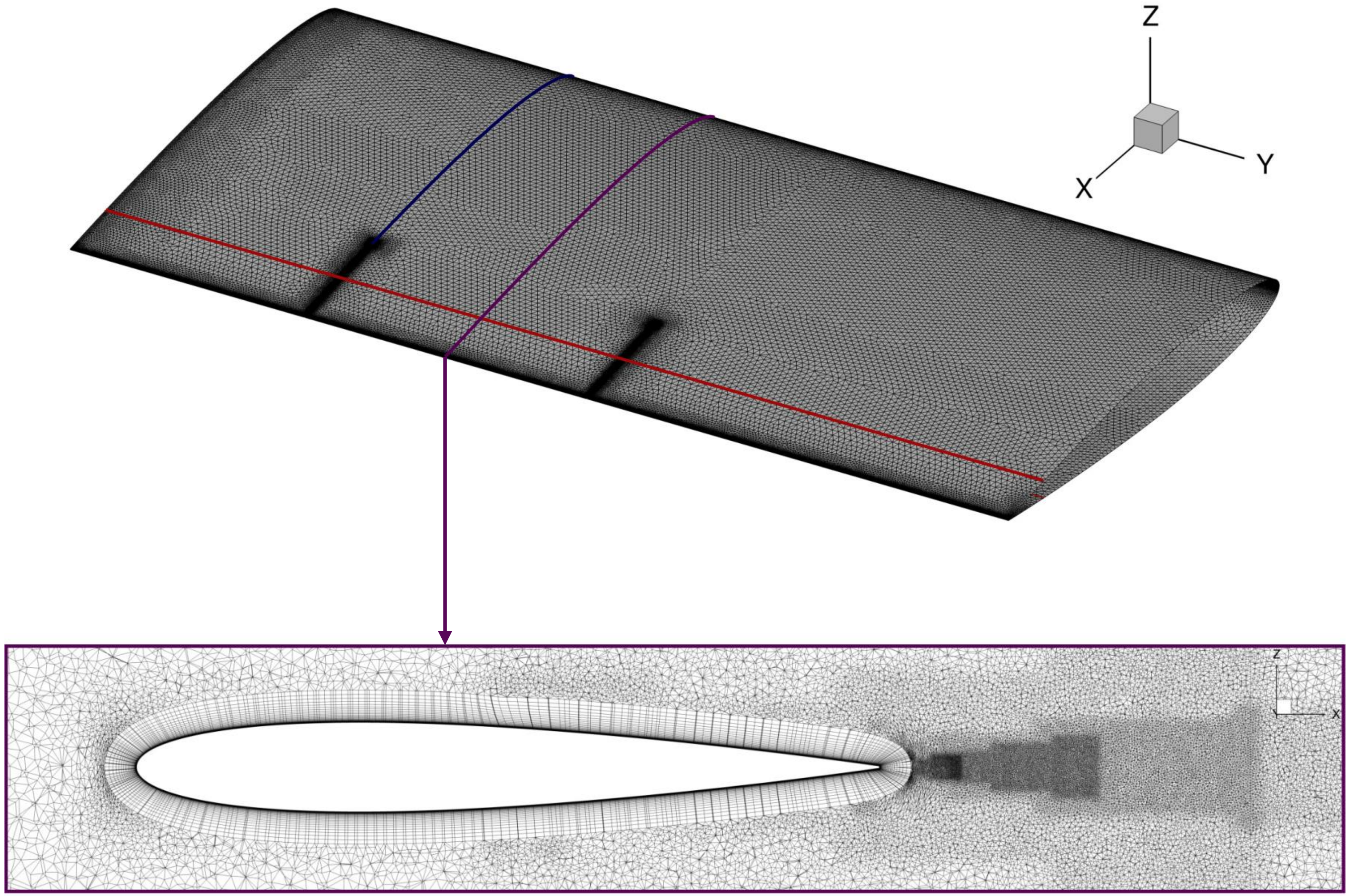
- Turbulence approach:
  - Improved delayed detached eddy simulation using SA RANS as the underlying model (SA IDDES)
  - Synthetic turbulence is injected at 6 different interfaces
    - Wall-modeled LES in the vicinity of the control surface



BACT test case
Mesh generation

RANS



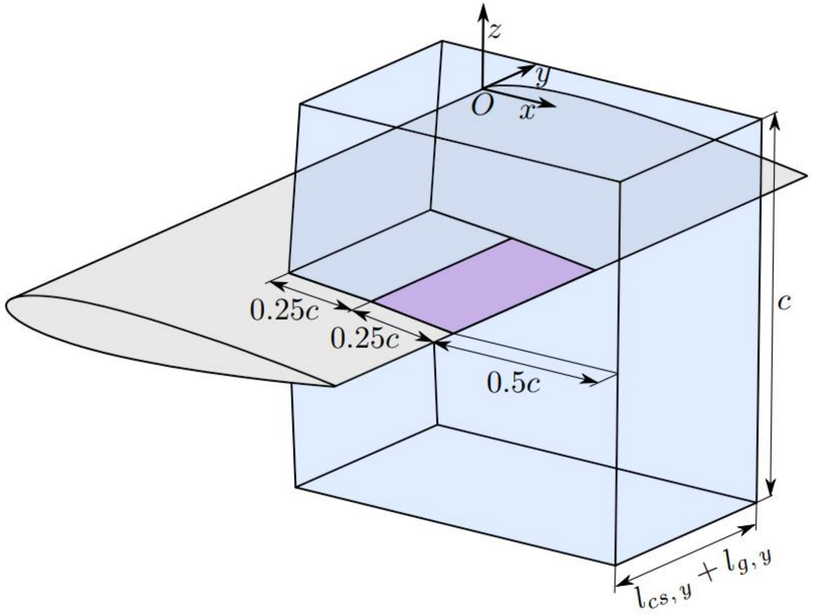


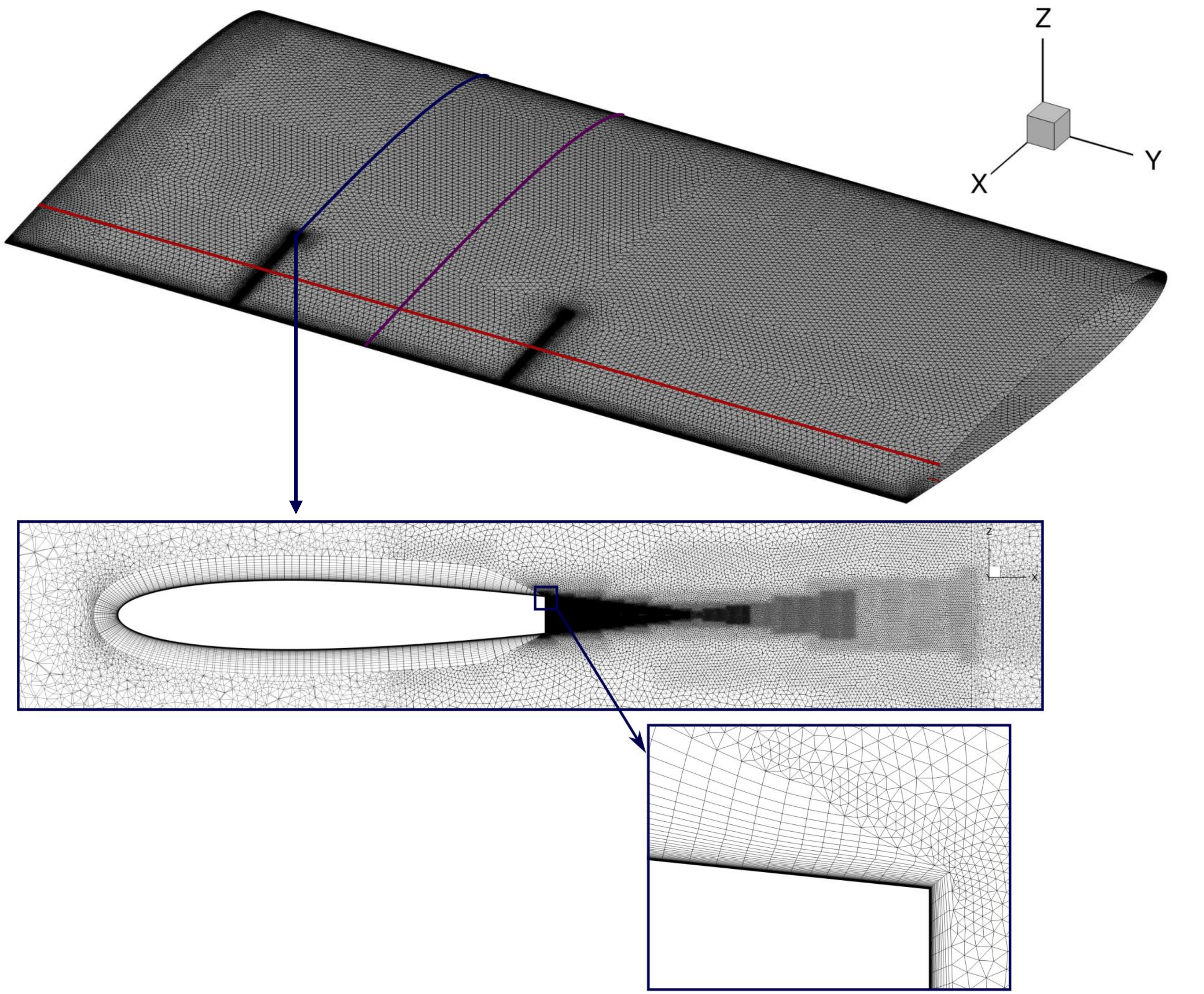
Wall distance of first element

$\Delta z_1 = 1.5e^{-3}\ \mathrm{m} \quad \rightarrow \quad z^+ \approx 1$

BACT test case
Mesh generation

RANS

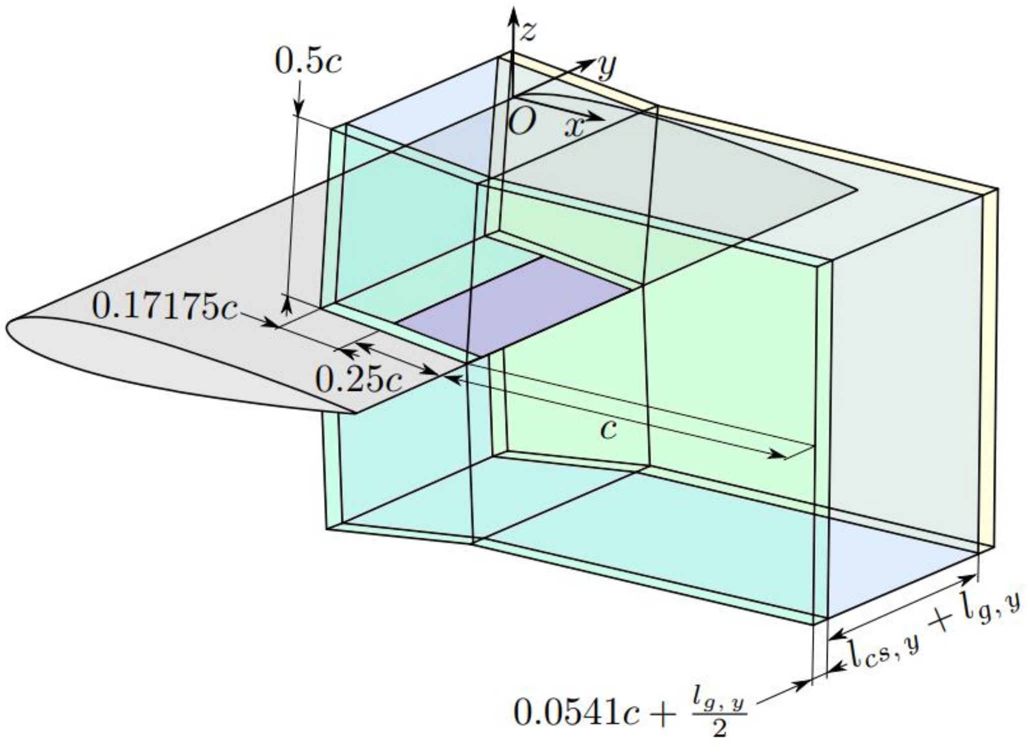




22.83 Million grid points

BACT test case
Mesh generation

HRLES



WMLES resolution [5]

$$\Delta x \approx \frac{\delta}{10} \qquad \Delta y \approx \frac{\delta}{20} \qquad \Delta z_{LES} = 1.5\ \delta_{local,max}$$

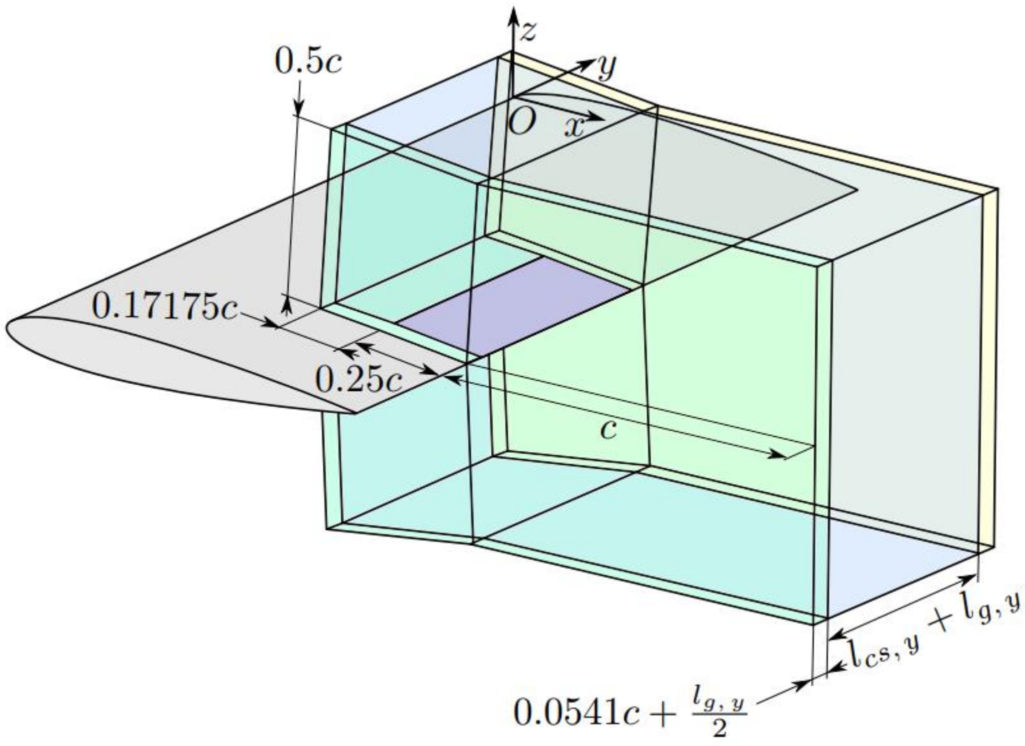
Exp. family	Experiment numbers	Ma	Re	q (N/m²)	α (°)	δ_{cs} (°)		
1	[8EST01, 8EST07]	0.65	$4.47e^6$	6942.64	0.01	−9.7	−4.8	−1.7
						0.3	2.3	5.3
						10.3		
2	[8EST08, 8EST14]	0.65	$4.48e^6$	6942.64	1.99	−9.8	−4.8	−1.7
						0.3	2.3	5.3
						10.3		
3	[8EST15, 8EST25]	0.77	$3.80e^6$	6846.88	0.03	−10.0	−5.0	−2.0
						0.0	0.5	1.0
						2.0	3.0	5.0
						10.0	12.0	
4	[8EST26, 8EST35]	0.77	$3.83e^6$	6942.64	3.99	−9.9	−5.0	−1.9
						0.0	1.0	2.0
						3.0	5.0	10.0
						12.0		

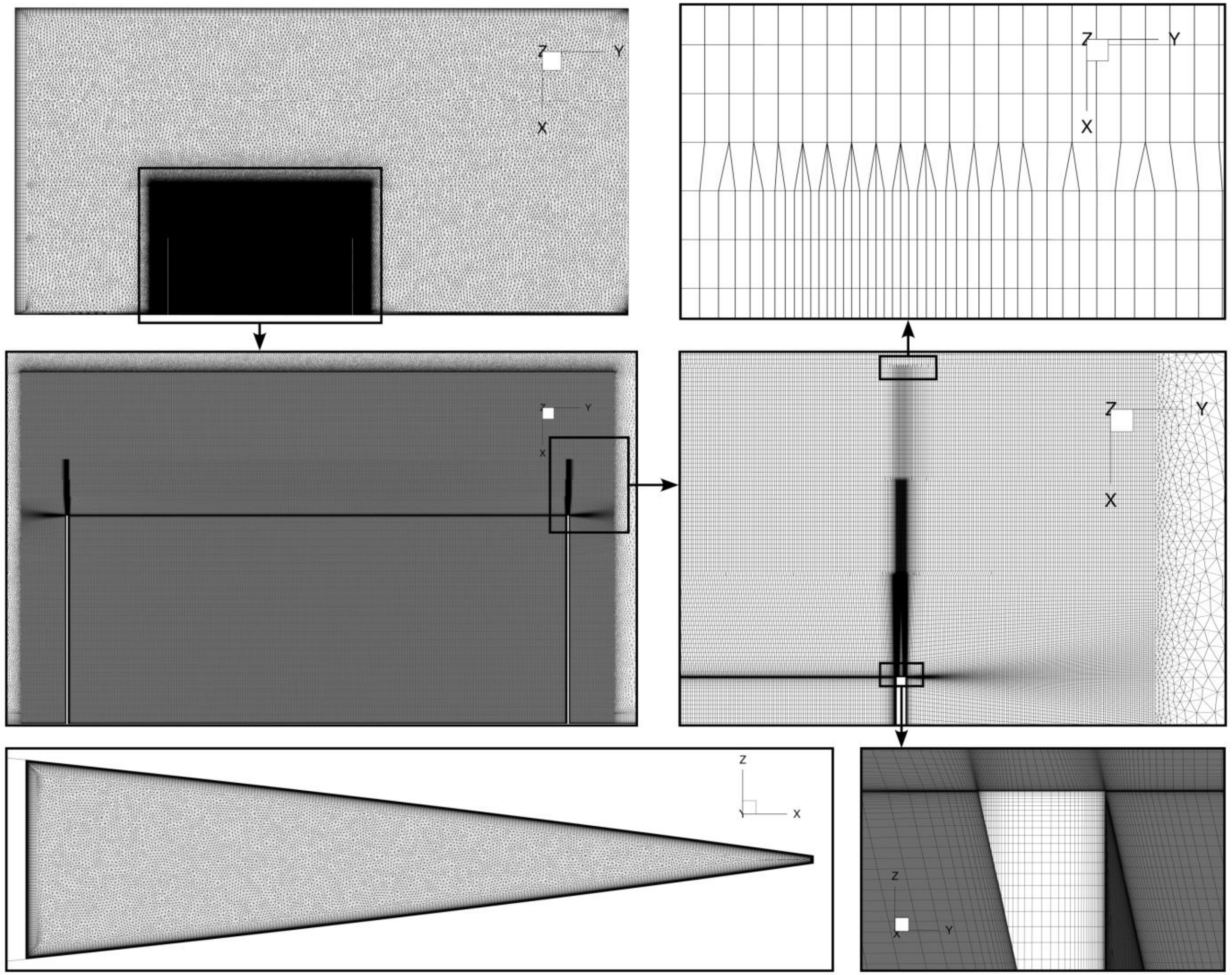
35 RANS simulations

[5] Larsson, J., Kawai, S., Bodart, J., and Bermejo-Moreno, I. (2016). LES with wall-stress modeling: progress and directions. *Mech. Eng. Rev.*, 3(1), 15-00418.

BACT test case
Mesh generation

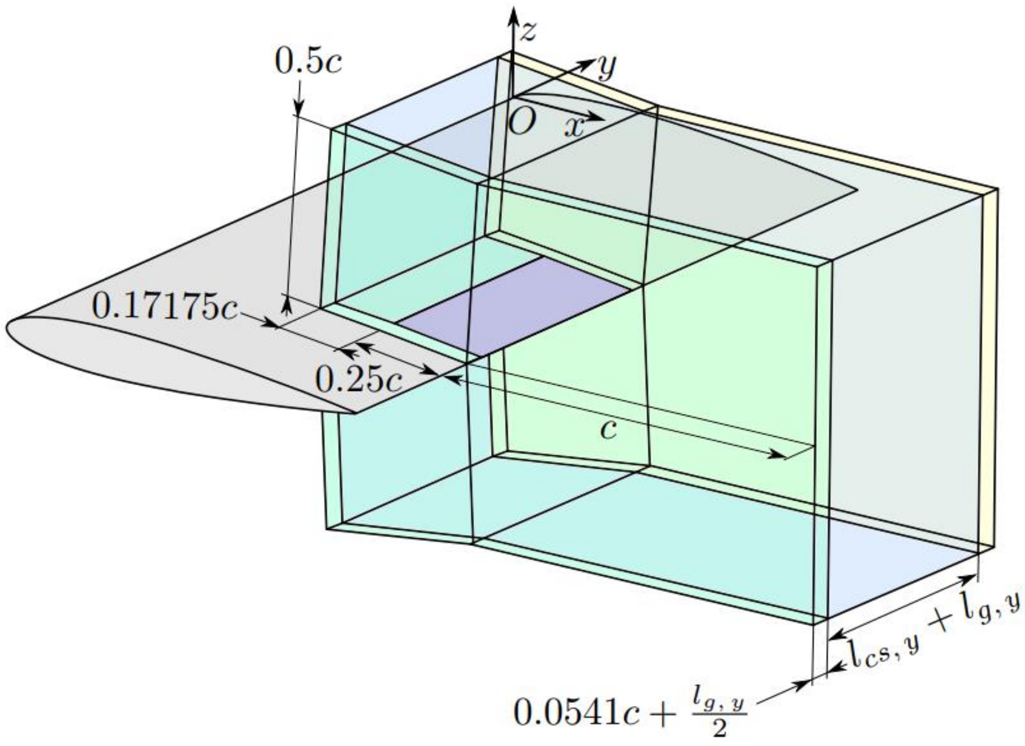
HRLES

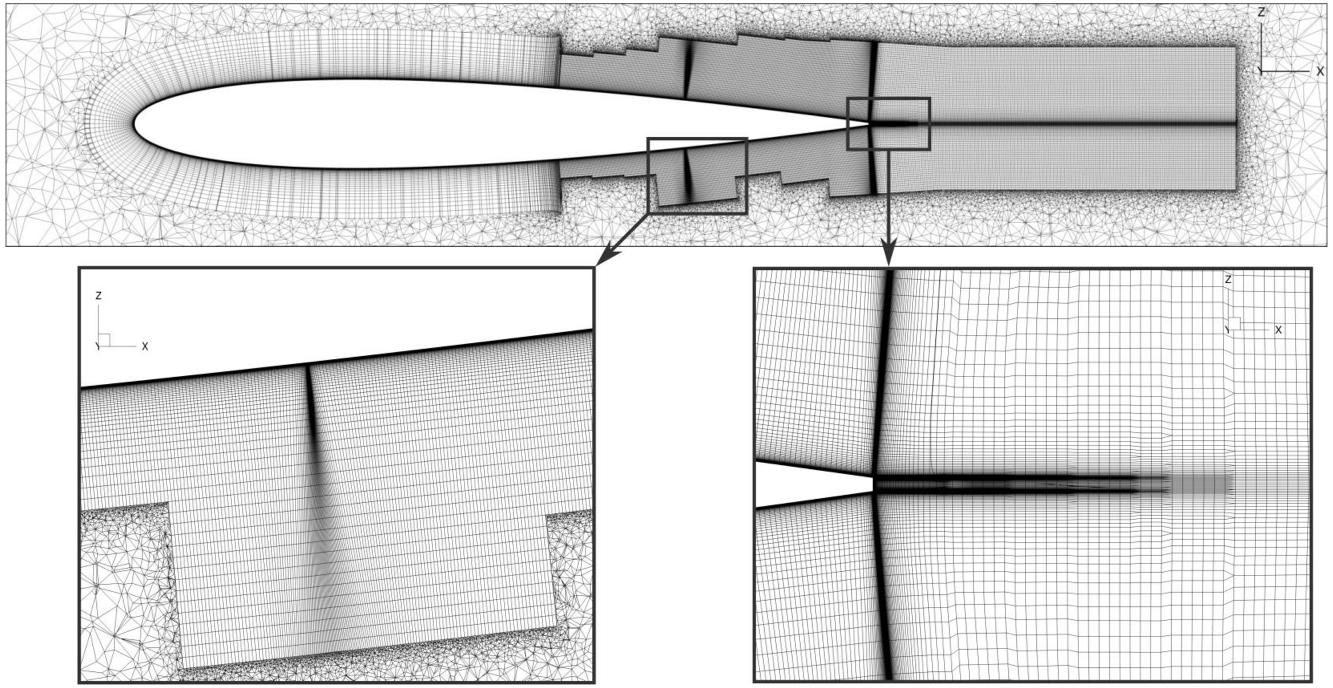




BACT test case
Mesh generation

HRLES





174 Million grid points

BACT test case

Numerical methods and flow conditions

- Two static control surface deployments:

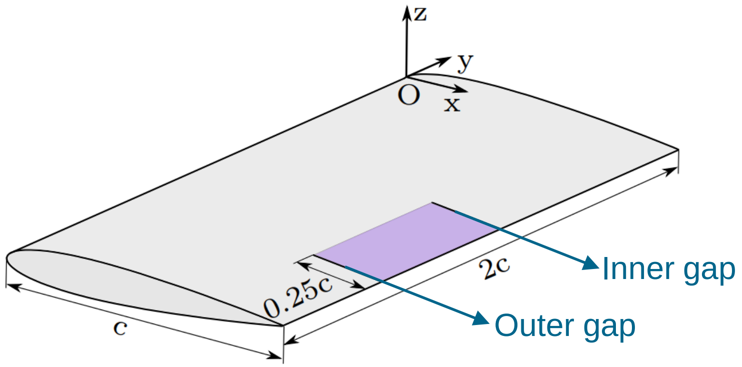
Experiment number	*Experiment family*	Ma	Re	q (N/m^2)	α (°)	δ_{cs} (°)
8EST26	4	0.770	$3.83e^6$	6952.21	3.99	-9.9
8EST33	4	0.769	$3.83e^6$	6961.79	3.99	5.0

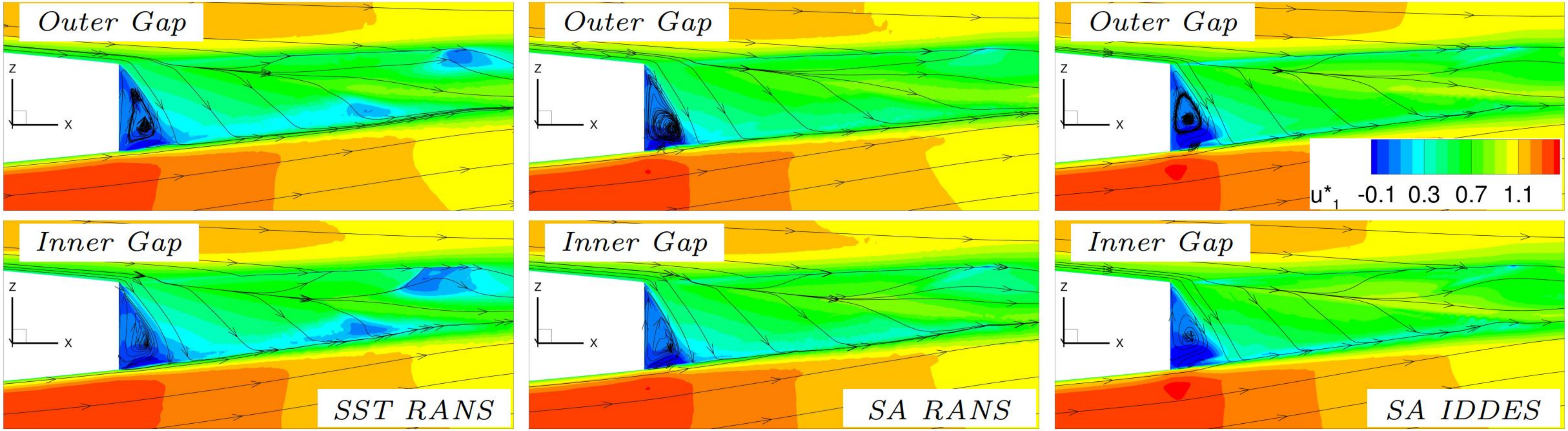
- CFD solver TAU
- RANS simulations
  - Central scheme with added matrix dissipation to discretize the convective fluxes
  - 640 processors
- HRLES simulations
  - Hybrid low-dissipation low-dispersion scheme (HLD2) to discretize the convective fluxes:
    - Central scheme with added matrix dissipation in RANS regions
    - LD2 scheme in LES regions
  - Implicit dual time stepping scheme with $CFL_{conv} = 1$
  - 6400 processors

BACT test case

8EST26 – Normalized streamwise velocity – Inner and outer gaps

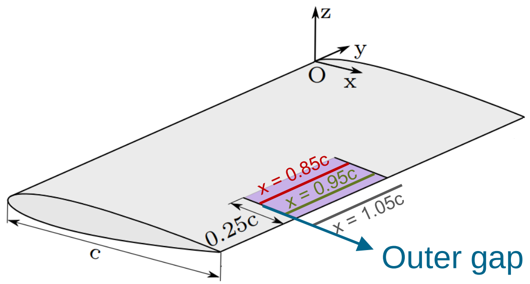
Experiment number	*Experiment family*	Ma	Re	q (N/m^2)	α (°)	δ_{cs} (°)
8EST26	4	0.770	$3.83e^6$	6952.21	3.99	−9.9

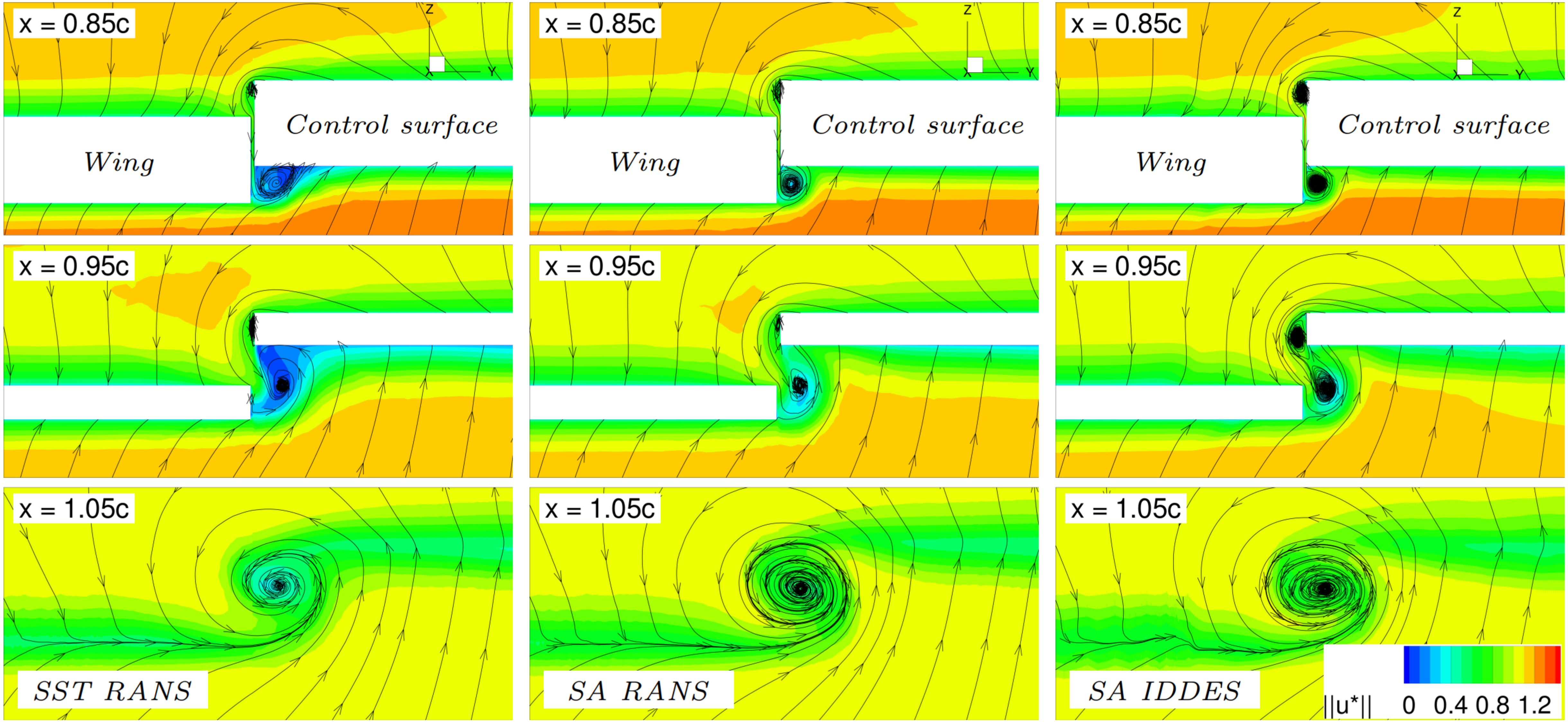




BACT test case

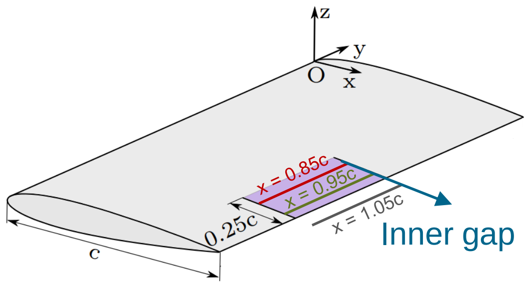
8EST26 – Normalized velocity magnitude – Outer gap

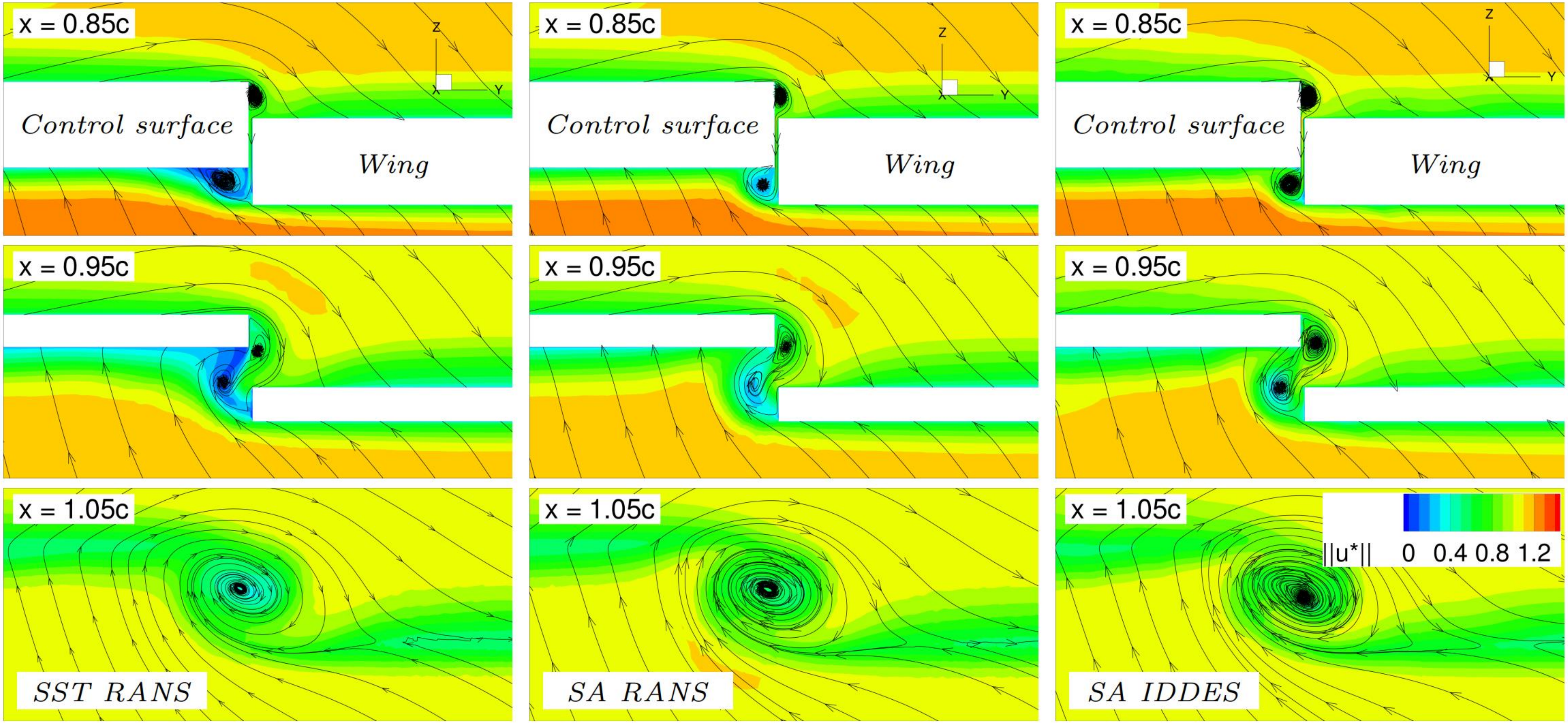




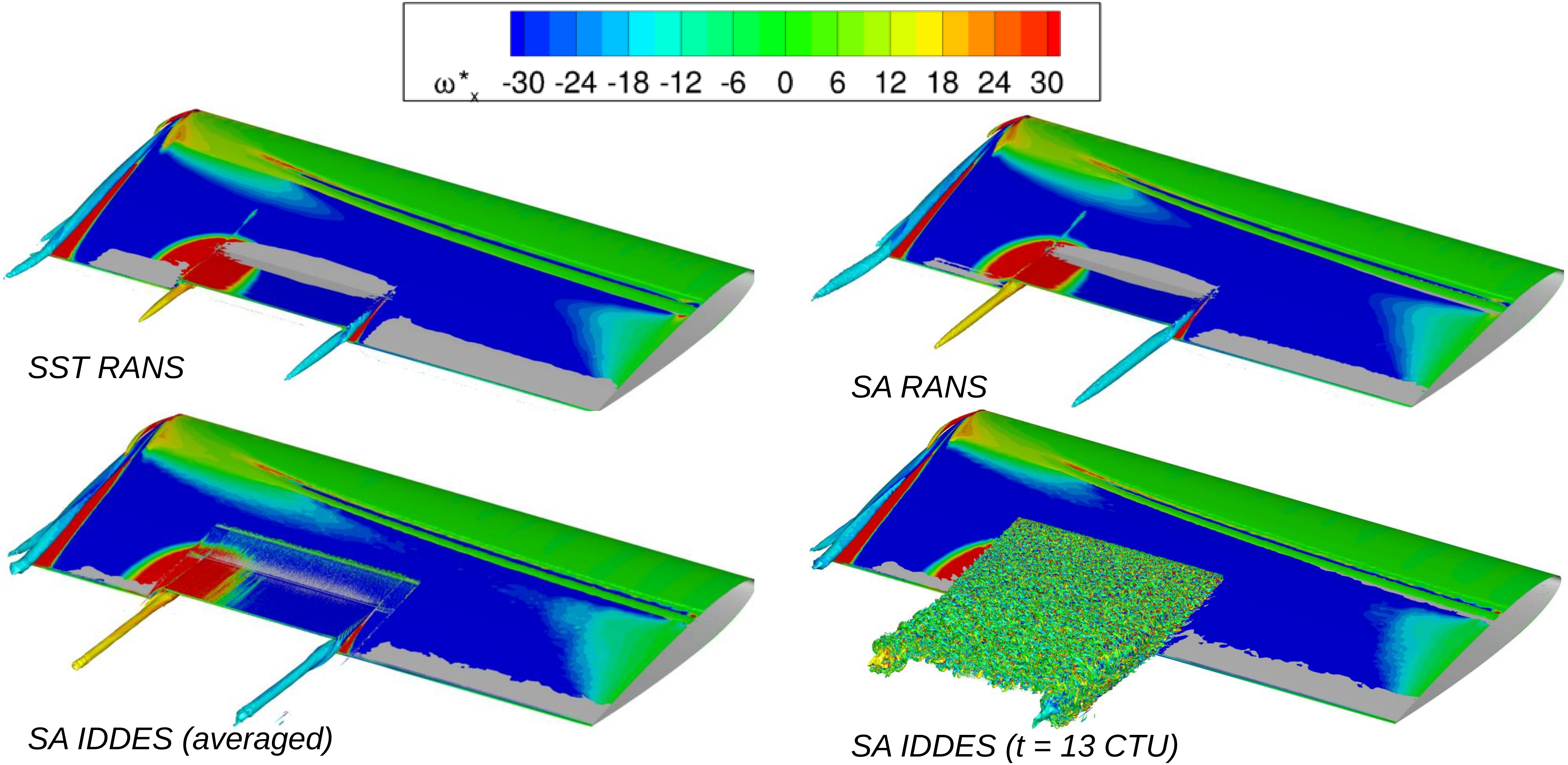
BACT test case

8EST26 – Normalized velocity magnitude – Inner gap



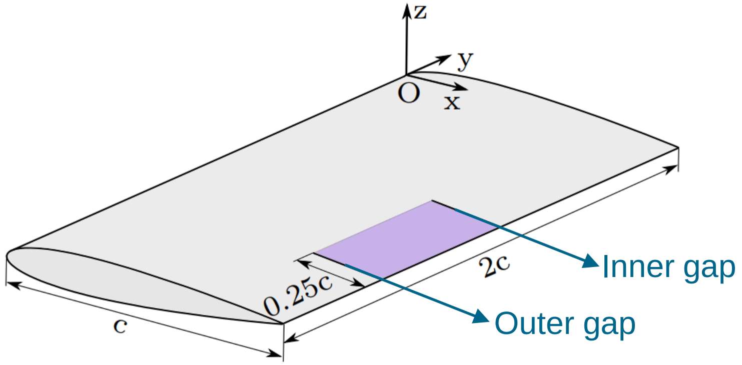


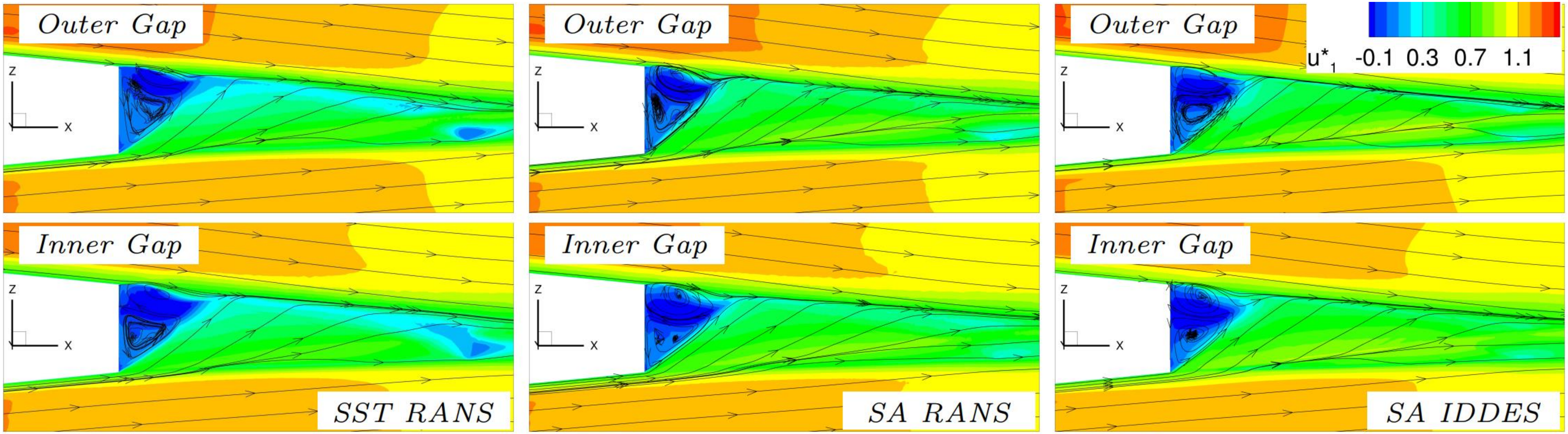
BACT test case
8EST26 – Isosurfaces with Q* = 60



BACT configuration
8EST33 – Normalized streamwise velocity – Inner and outer gaps

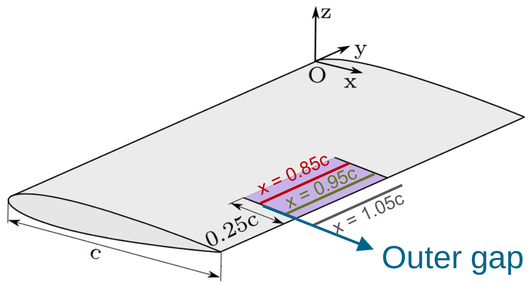
Experiment number	*Experiment family*	Ma	Re	q (N/m^2)	α (°)	δ_{cs} (°)
8EST33	4	0.769	$3.83e^6$	6961.79	3.99	5.0

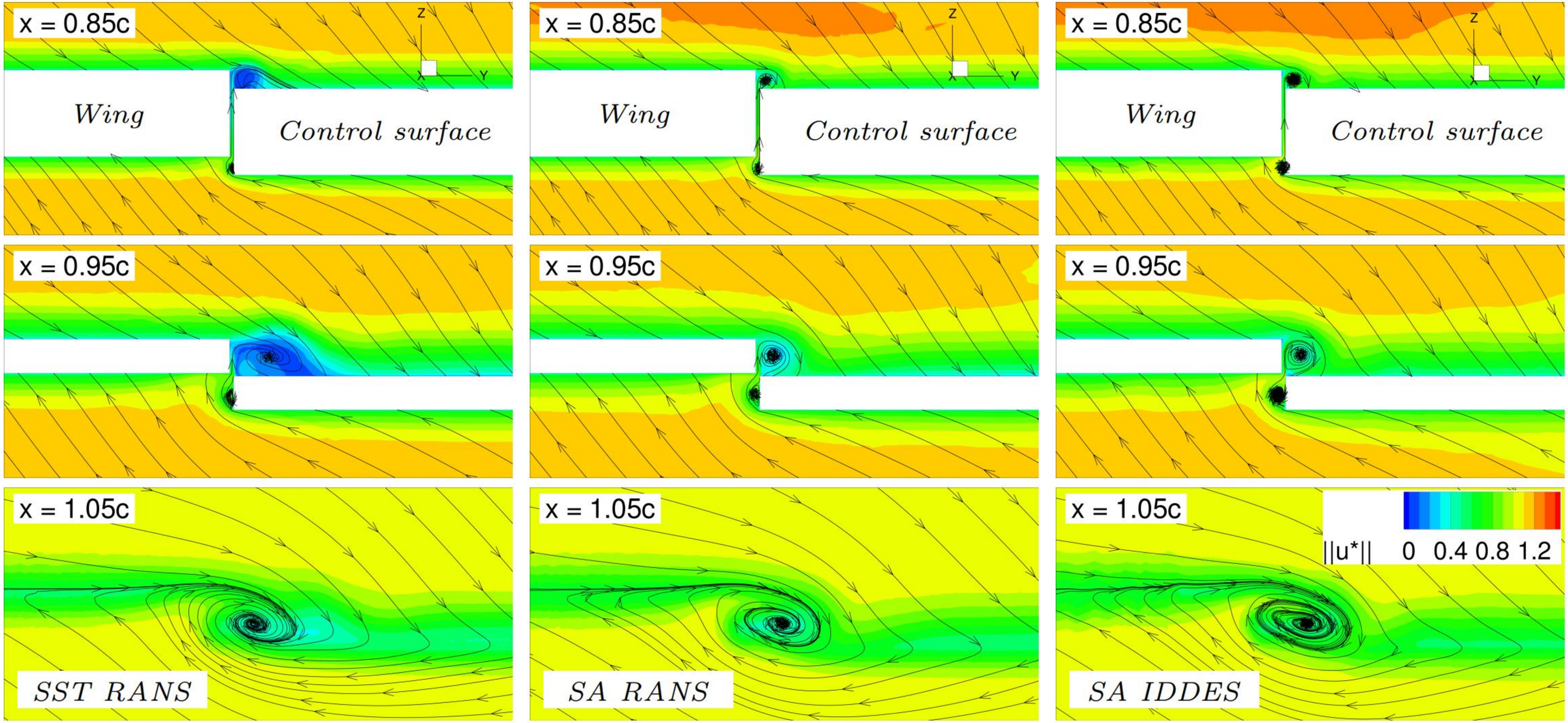




BACT configuration

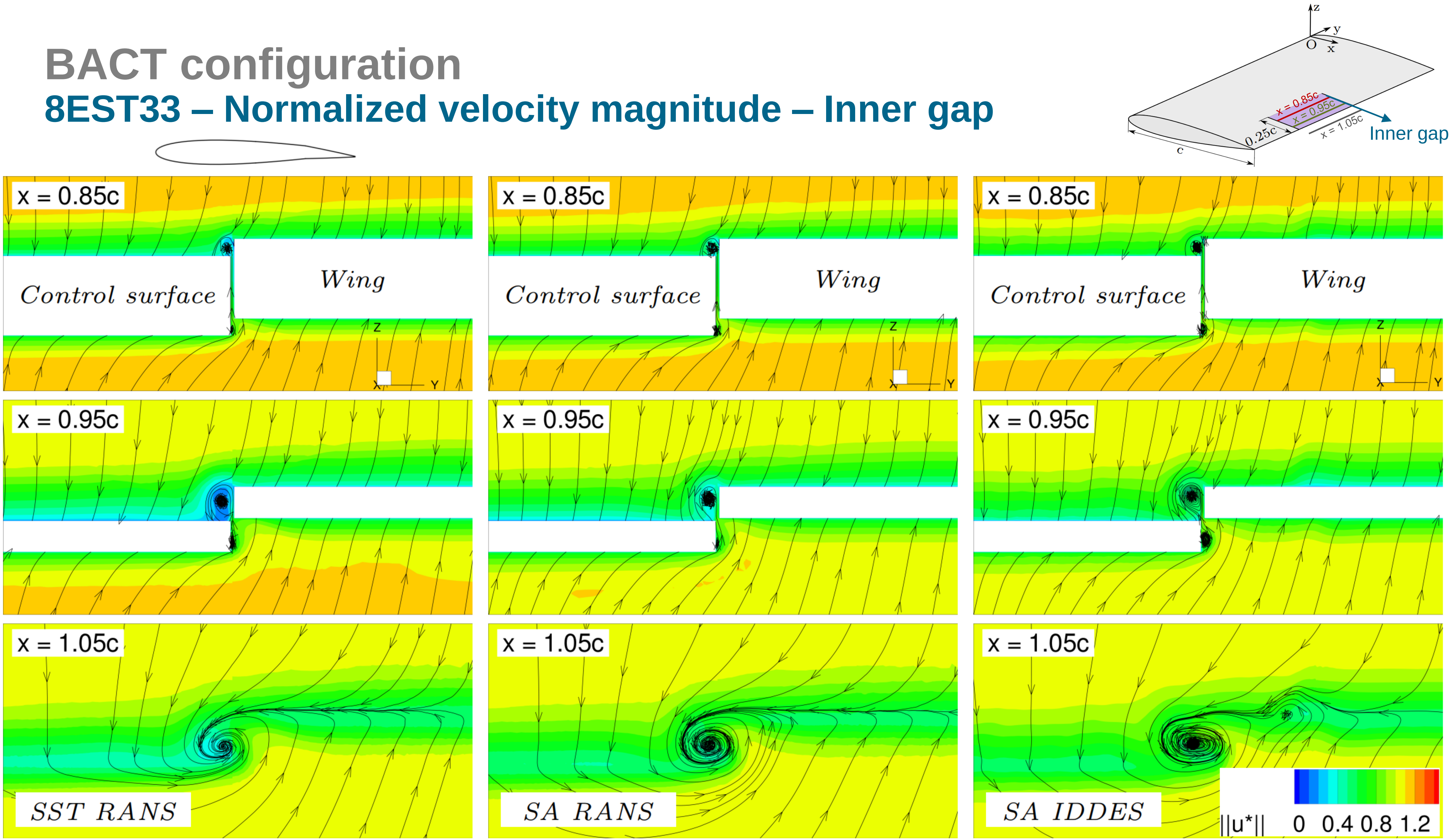
8EST33 – Normalized velocity magnitude – Outer gap



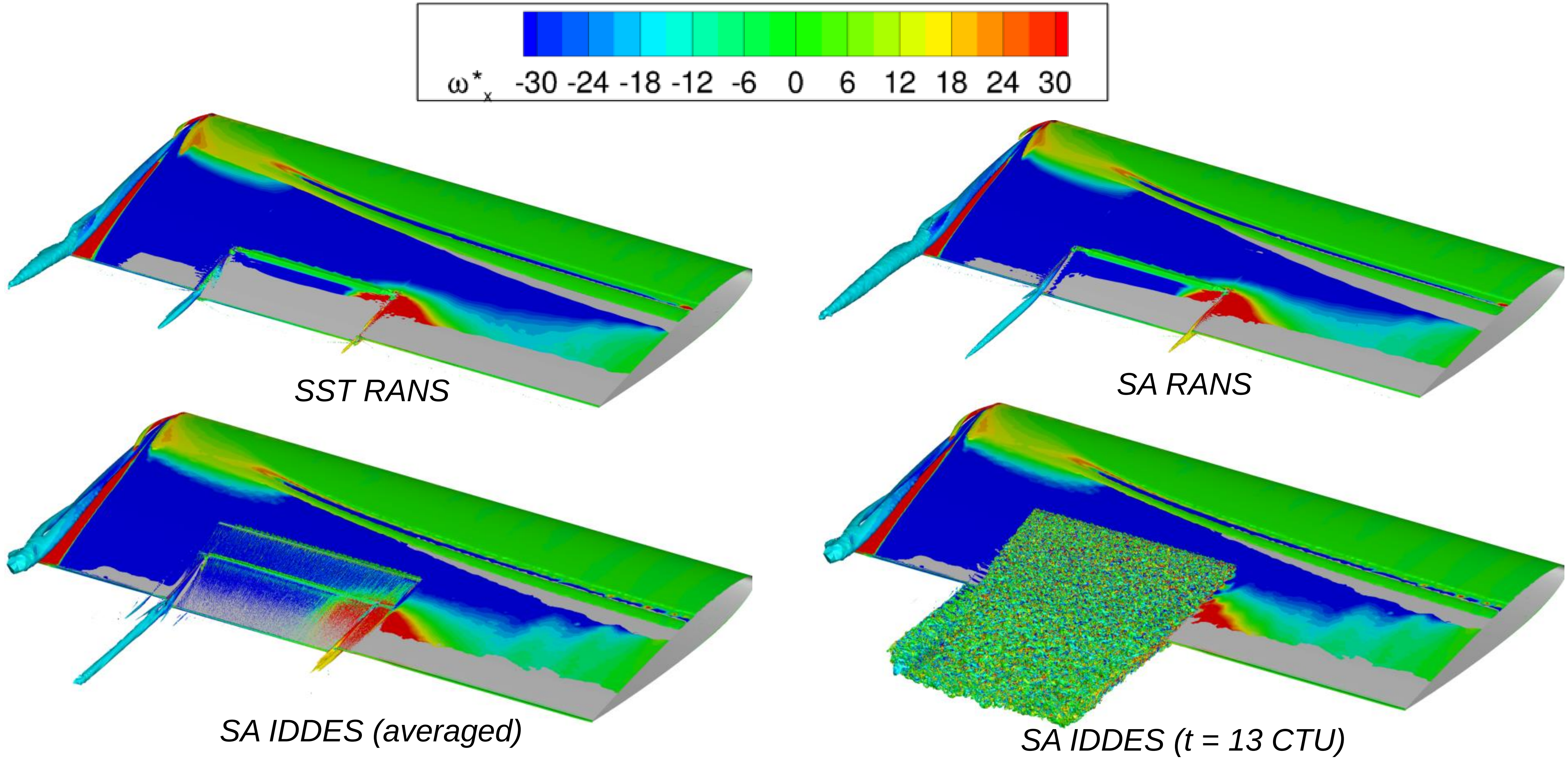


BACT configuration

8EST33 – Normalized velocity magnitude – Inner gap

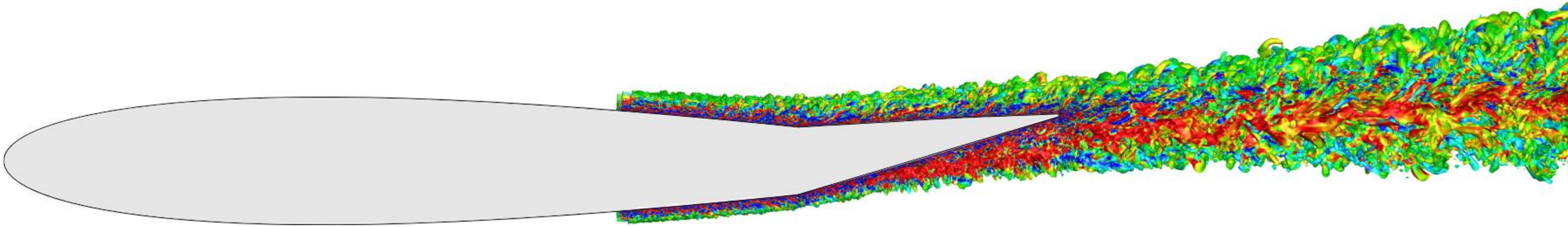


BACT configuration
8EST33 – Isosurfaces with Q* = 60



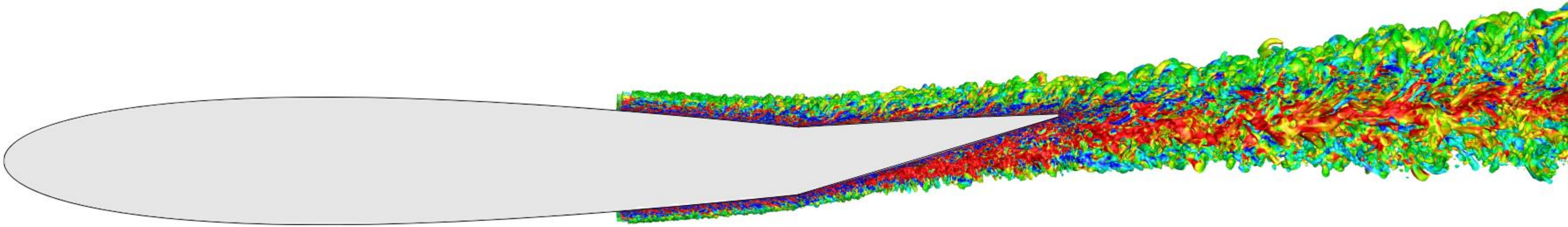
Conclusions

- Presence of spanwise gaps significantly alter the flow circulation:
  - Upward-deflected trailing edge control surface:
    - Downward spanwise gap flow
    - Clockwise inner gap streamwise vortex
    - Counterclockwise outer gap streamwise vortex
  - Downward-deflected trailing edge control surface:
    - Upward spanwise gap flow
    - Counterclockwise inner gap streamwise vortex
    - Clockwise outer gap streamwise vortex
  - Control surface deflection angle impacts vortex size and spanwise recirculation zones



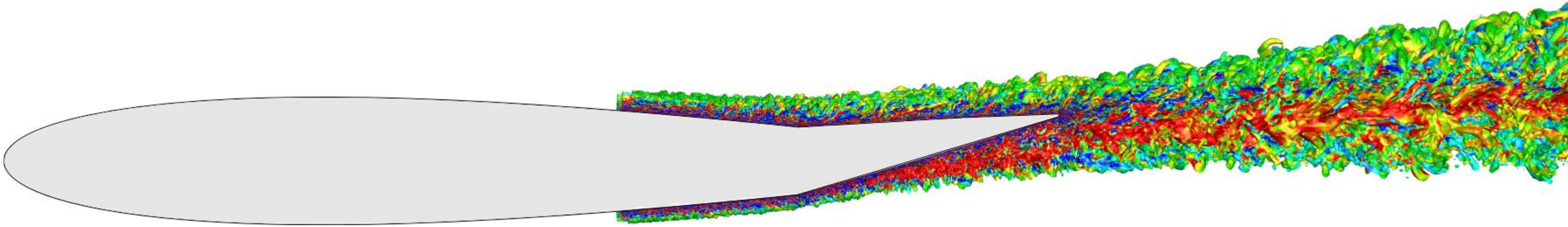
Conclusions

- Turbulence modeling:
  - SA RANS and SA IDDES models showed consistent results;
    - SA RANS is efficient for such small deflection angles
  - SST RANS showed some discrepancies
    - Consistency between SA RANS and SA IDDES could be related to the usage of the SA model in the RANS regions



Outlook

- Explore SST-based IDDES model to assess influence of underlying RANS model on IDDES predictions for spanwise gap flows.
- Investigate wall-modeled LES for larger deflection angles to better understand flow separation and turbulence model limitations in control surface simulations.



Thank you!

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