RBF Morph Advanced Mesh Morphing for optimization and multi-physics

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Tor Vergata

(rbf-morph)™

Outline

- RBF Morph tool presentation
- Industrial Applications
- Generic Formula 1 Front End
- Ice accretion
- FSI using modal approach

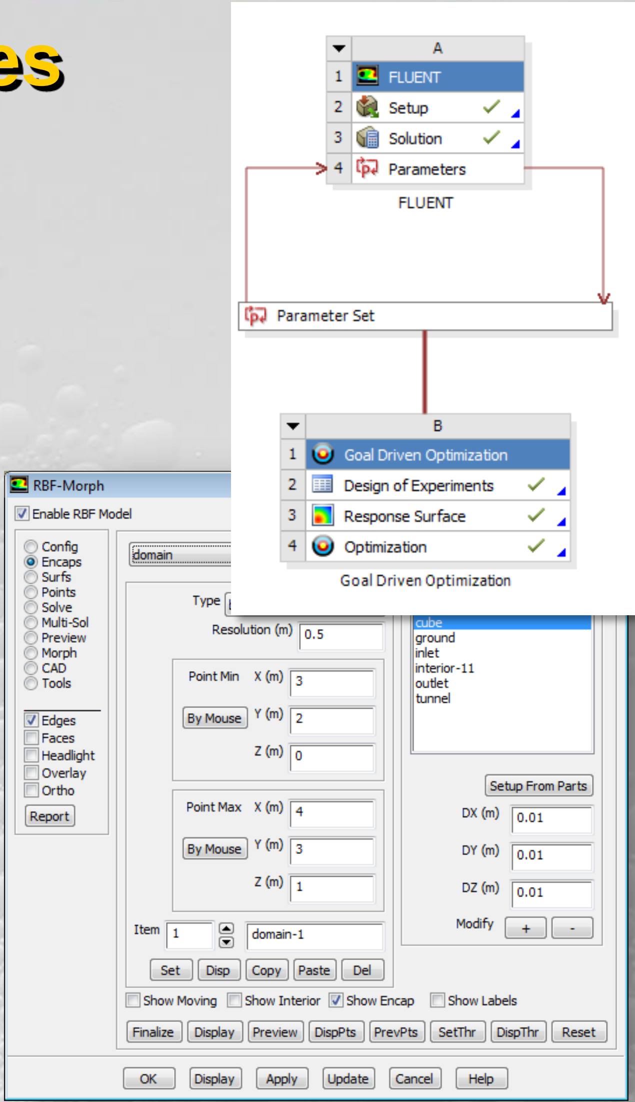
RBF Morph tool presentation

Morphing & Smoothing

- A mesh morpher is a tool capable to perform **mesh modifications**, in order to achieve arbitrary shape changes and related volume smoothing, without changing the mesh topology.
- In general a morphing operation can introduce a reduction of the **mesh quality**
- A **good** morpher has to minimize this effect, and maximize the possible shape modifications.
- If mesh quality is well preserved, then using the same mesh structure it’s a **clear benefit** (remeshing introduces **noise**!).

RBF Morph Features

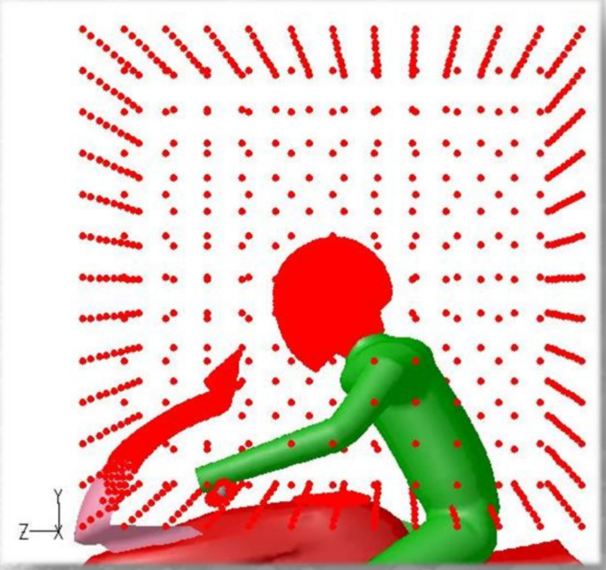
- **Add on** fully integrated within **Fluent** (GUI, TUI & solving stage) and **Workbench**
- **Mesh-independent** RBF fit used for surface mesh morphing and volume mesh smoothing
- **Parallel** calculation allows to morph **large size** models (many millions of cells) in a short time
- Management of **every kind of mesh** element type (tetrahedral, hexahedral, polyhedral, etc.)
- Support of the **CAD re-design** of the morphed surfaces
- **Multi fit** makes the Fluent case truly parametric (only 1 mesh is stored)
- **Precision**: exact nodal movement and exact feature preservation (**RBF** are better than **FFD**).



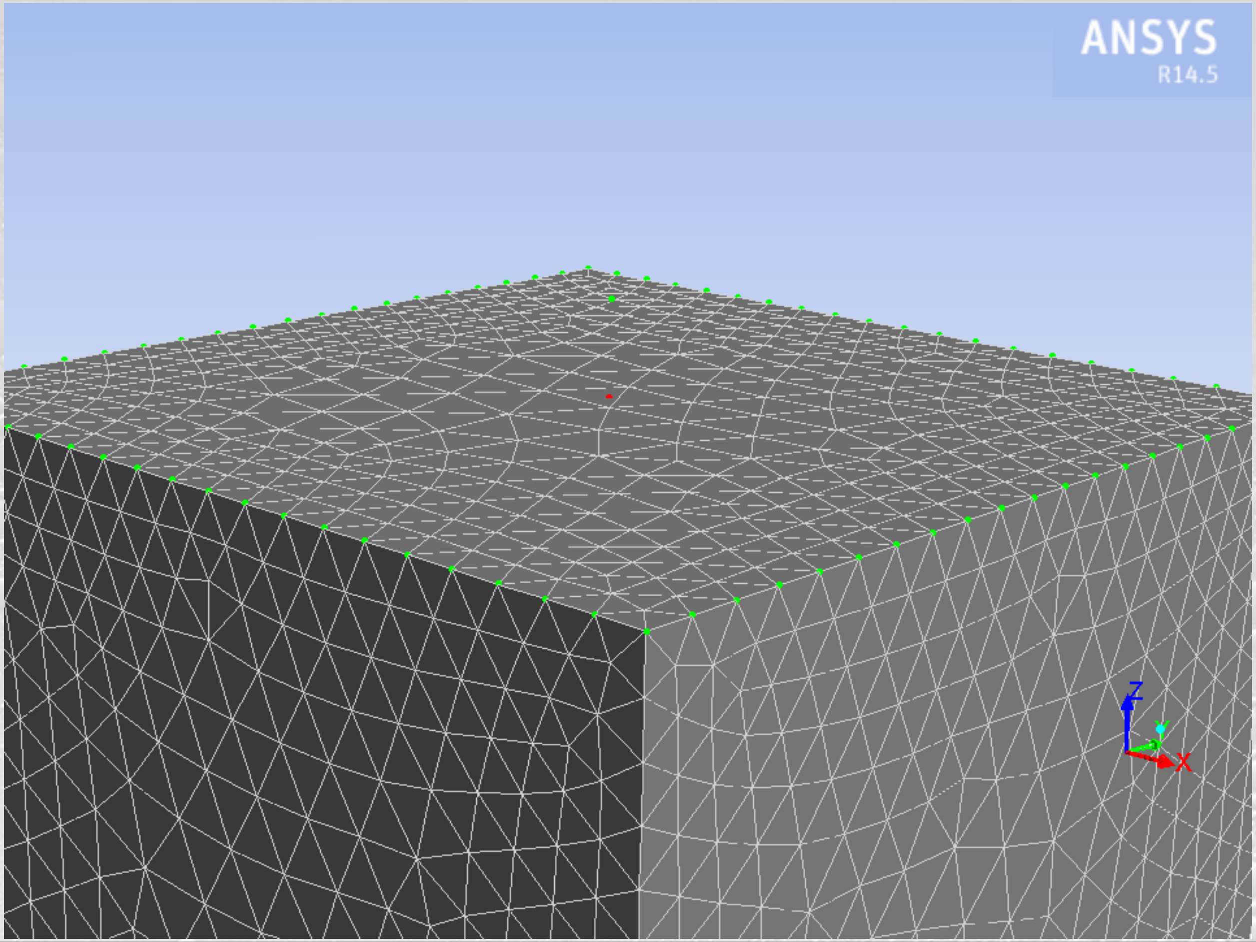
Mesh Morphing with Radial Basis Functions

- A system of **radial functions** is used to **fit** a **solution** for the mesh movement/morphing, from a list of **source points** and their **displacements**.
- The RBF problem definition does not depend on the mesh
- Radial Basis Function interpolation is used to derive the displacement in **any location** in the space, each component of the displacement is interpolated:

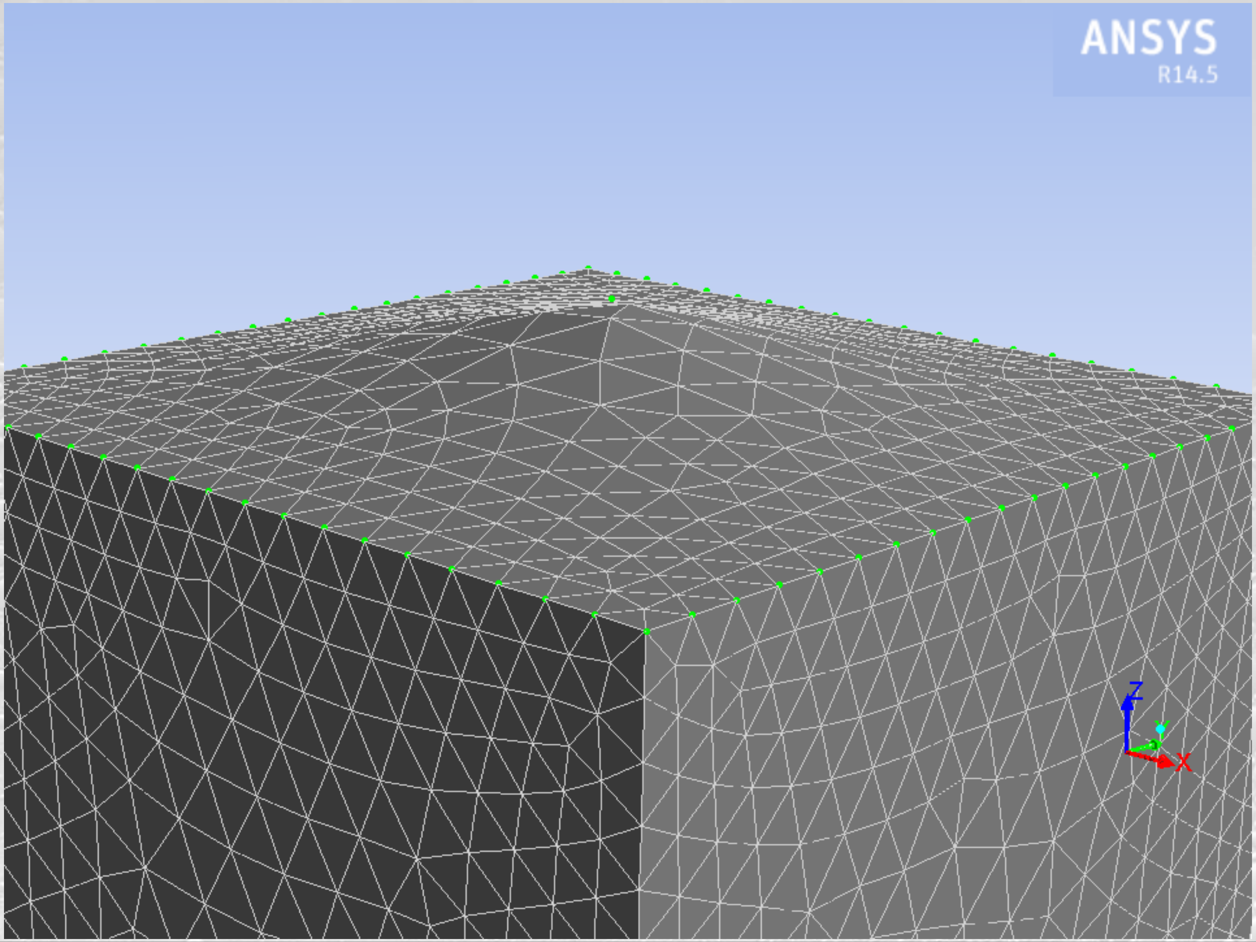
$$\begin{cases} v_x = s_x(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^x \phi\left(\left\|\mathbf{x} - \mathbf{x}_{k_i}\right\|\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ v_y = s_y(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^y \phi\left(\left\|\mathbf{x} - \mathbf{x}_{k_i}\right\|\right) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ v_z = s_z(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^z \phi\left(\left\|\mathbf{x} - \mathbf{x}_{k_i}\right\|\right) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$



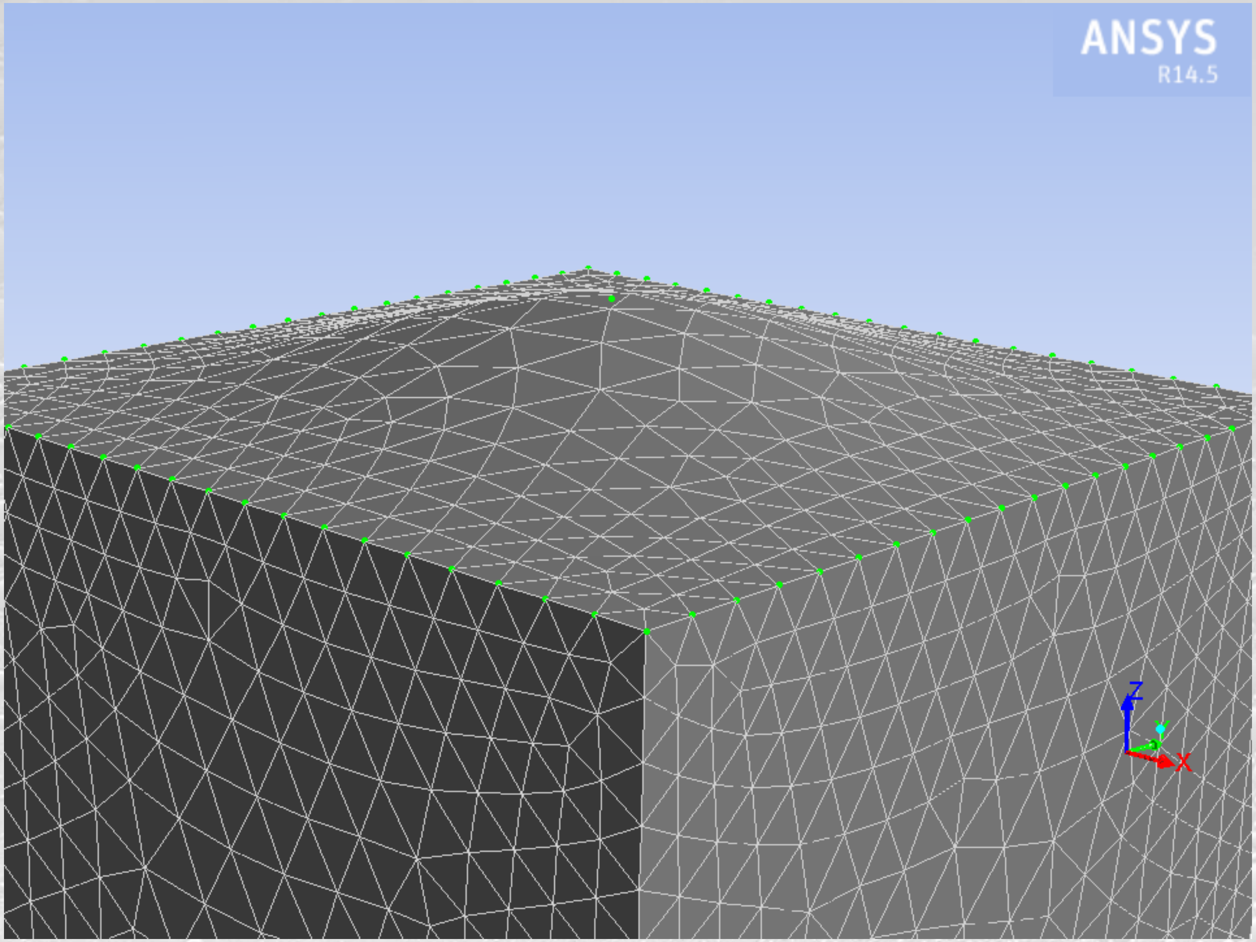
One pt at center 80 pts at border



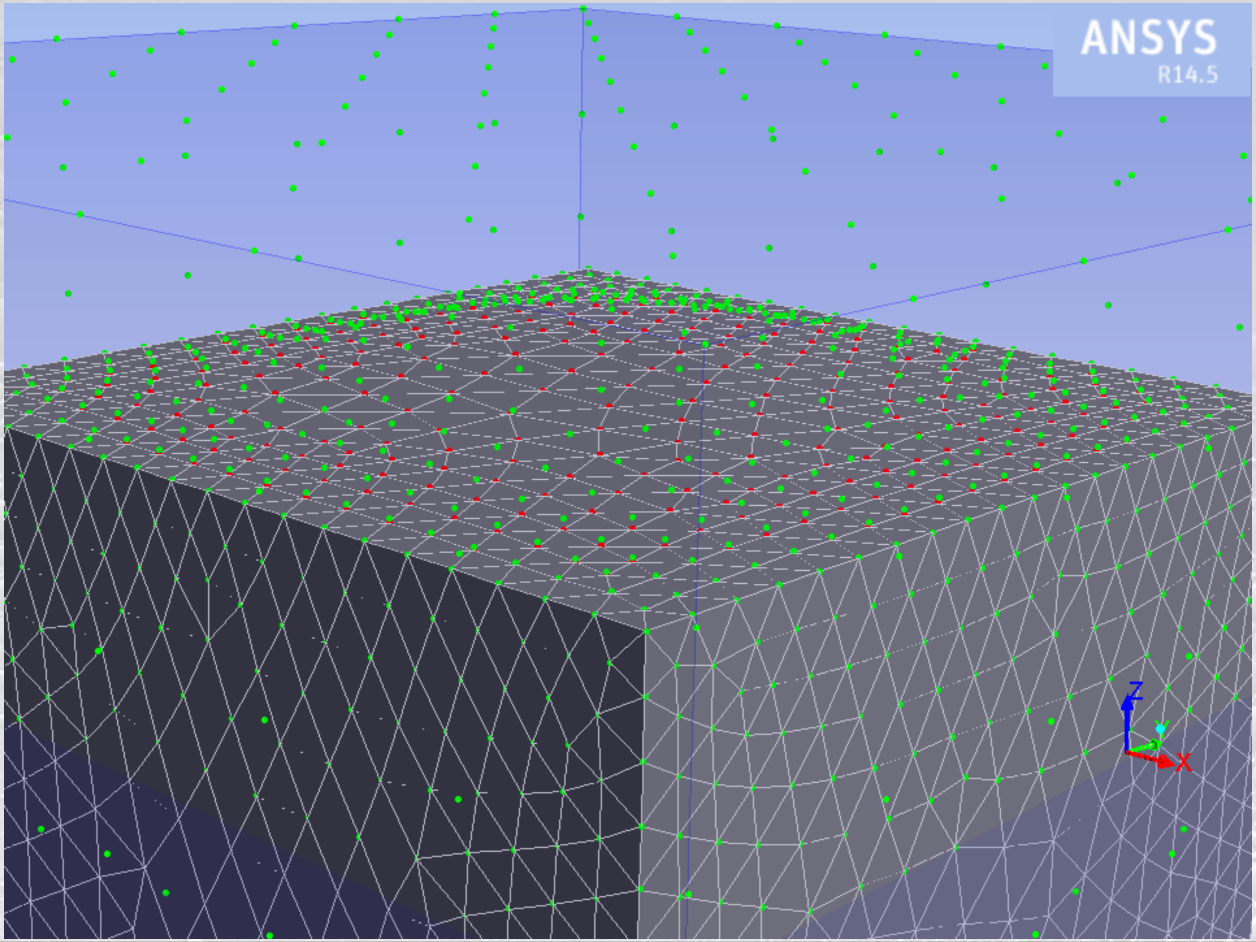
Effect on surface (gs-r)



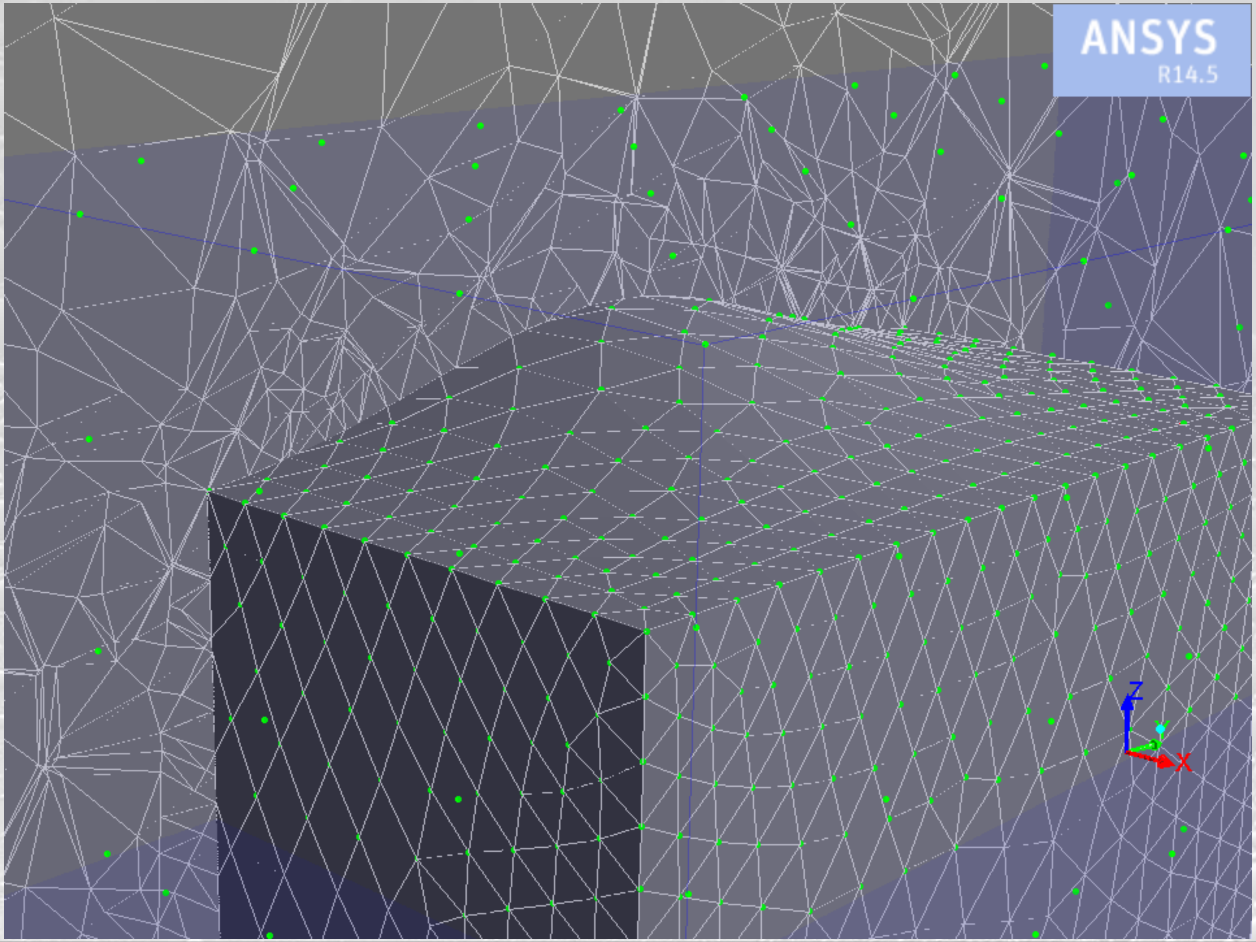
Effect on surface (cp-c4)



Control of volume mesh (1166 pts)

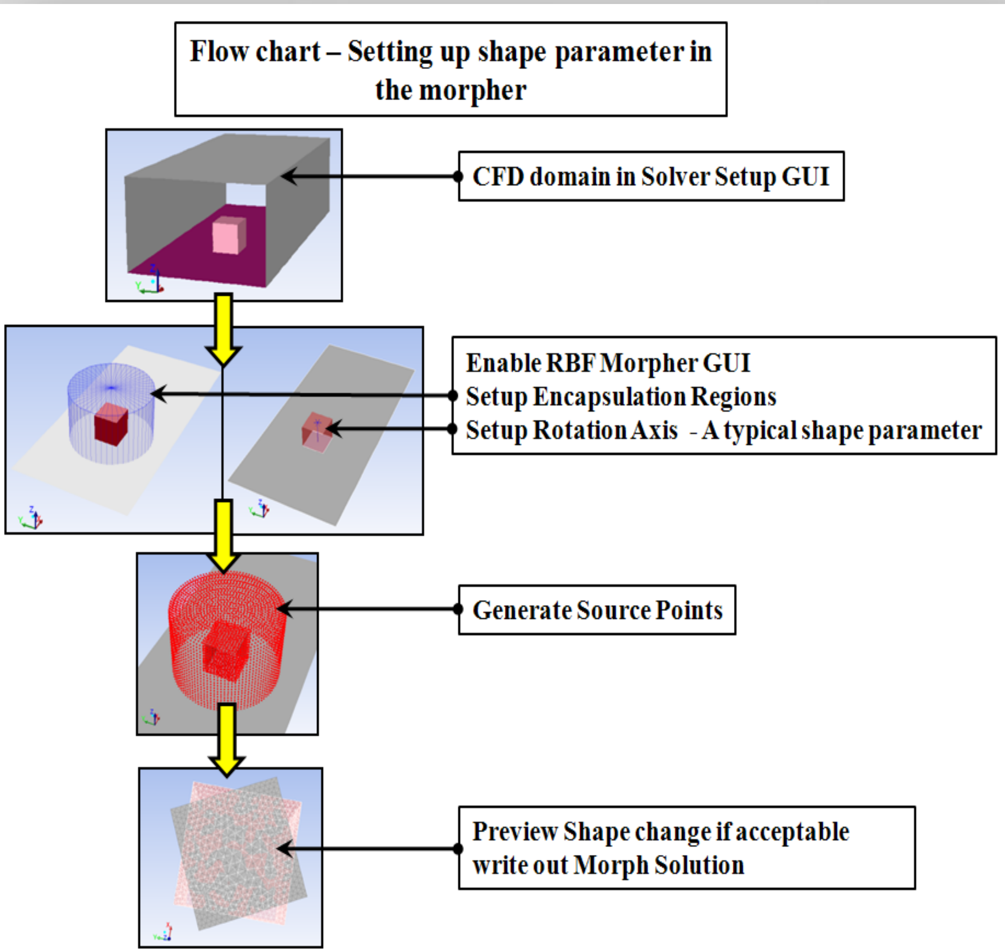


Morphing the volume mesh



How it Works: the problem setup

- The problem must describe correctly the **desired changes** and must **preserve exactly** the fixed part of the mesh.
- The prescription of the **source points** and their displacements fully defines the *RBF Morph* problem.
- Each problem and its fit define a mesh **modifier** or a **shape parameter**.



Background: accelerating the solver

- The evaluation of RBF at a point has a cost of order N
- The fit has a cost of order $\mathbf{N^3}$ for a direct fit (full populated matrix); this limit to ~10.000 the number of source points that can be used in a practical problem
- Using an iterative solver (with a good pre-conditioner) the fit has a cost of order $\mathbf{N^2}$; the number of points can be increased up to ~70.000
- Using also space partitioning to accelerate fit and evaluation the number of points can be increased up to ~**300.000**
- The method can be further accelerated using fast pre-conditioner building and FMM RBF evaluation…

Background: solver performances escalation

- 10.000 RBF centers FIT
  - 120 minutes Jan 2008
  - 5 seconds Jan 2010
- Largest fit **2.600.000** 133 minutes
- Largest model morphed **300.000.000** cells
- Fit and Morph a **100.000.000** cells model using **500.000** RBF centers within **15 minutes**

#points	2010 (Minutes)	2008 (Minutes)
3.000	0 (1s)	15
10.000	0 (5s)	120
40.000	1 (44s)	Not registered
160.000	4	Not registered
650.000	22	Not registered
2.600.000	133	Not registered

NVIDIA

Coming soon: GPU acceleration!

- Single RBF complete evaluation
- Unit random cube
- **GPU**: Kepler 20 2496 CUDA Cores GPU Clock 0.71 GHz
- **CPU**: quad core Intel(R) Xeon(R) CPU E5-2609 0 @ 2.40GHz

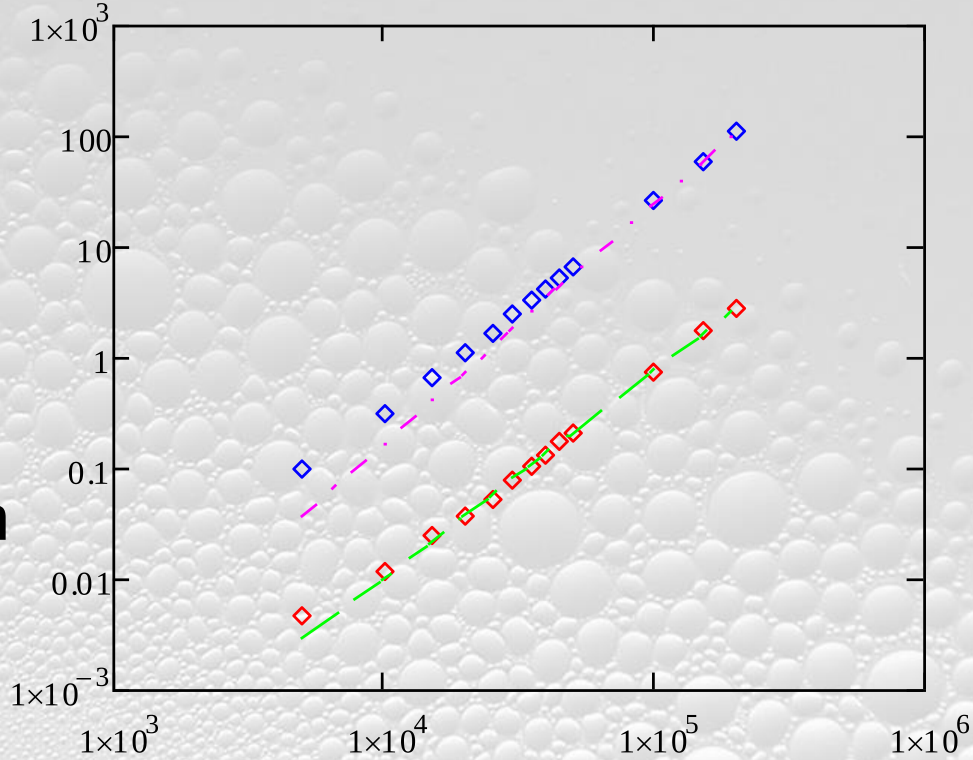
#points	CPU	GPU	speed up
5000	0,098402	0,004637	21,2
10000	0,319329	0,011746	27,2
15000	0,667639	0,024982	26,7
20000	1,135127	0,038352	29,6
25000	1,721781	0,054019	31,9
30000	2,451661	0,079459	30,9
35000	3,306897	0,108568	30,5
40000	4,286706	0,134978	31,8
45000	5,390029	0,181181	29,7
50000	6,707721	0,2135	31,4
100000	26,13633	0,745482	35,1
150000	58,96981	1,735367	34,0
200000	115,3628	2,861737	40,3

Scaling plot

- Complexity is expected to grow as **N ^{2}**
- GPU observed as **N $^{1.87}$**
- CPU observed as **N $^{2.174}$**
- Estimation at one million points:

  GPU: 59 s

  CPU: 2783 s

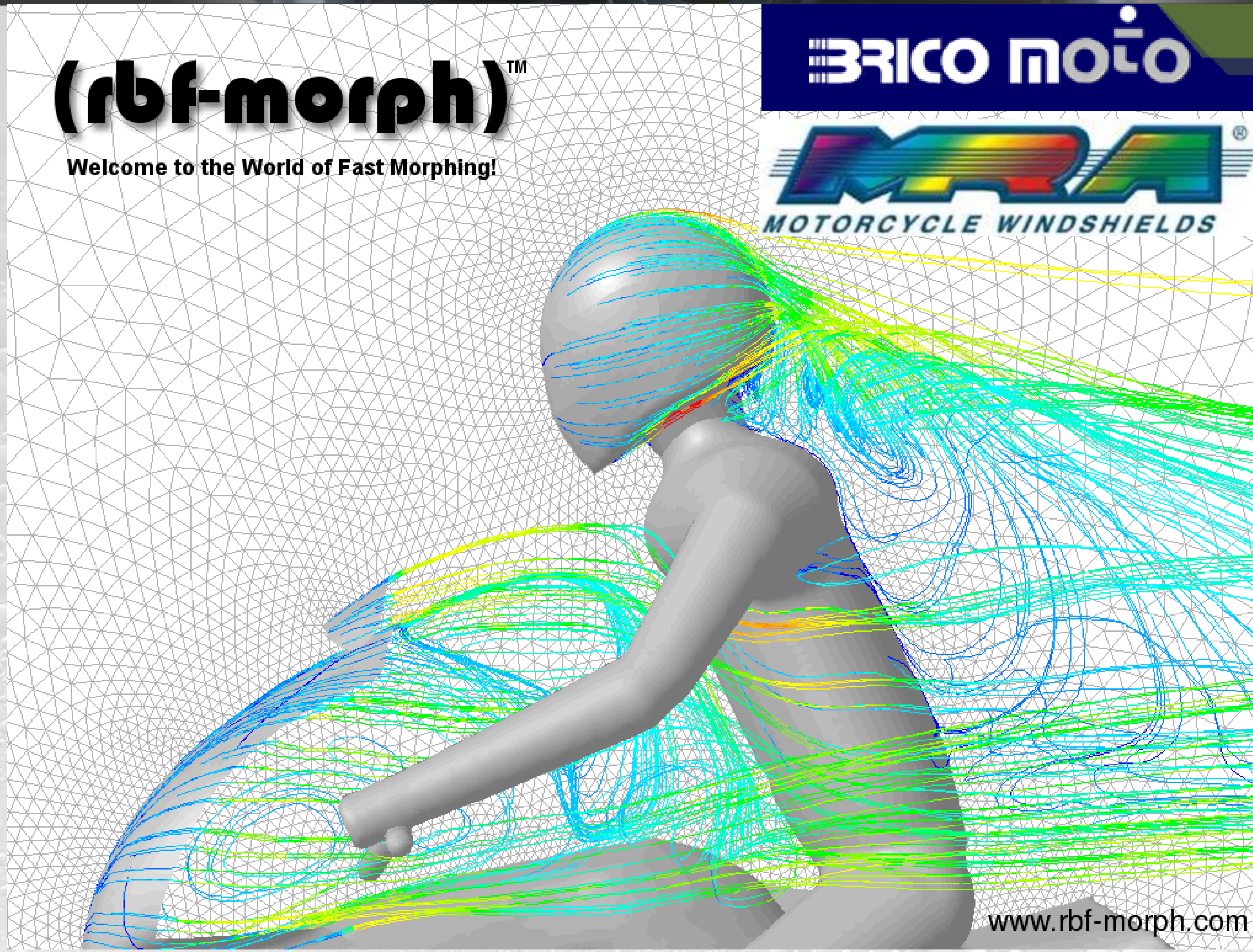


Industrial Applications

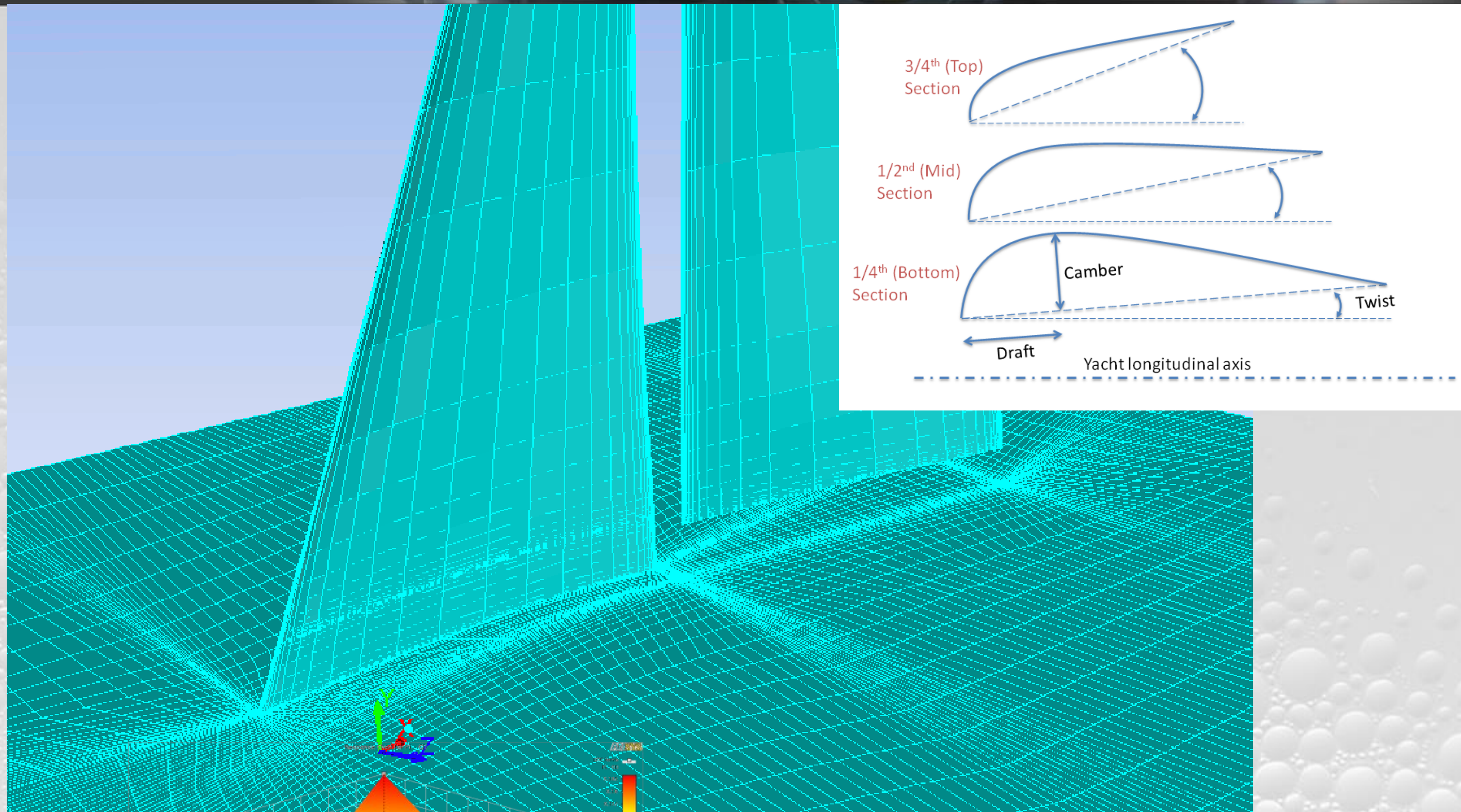
(rbf-morph)™
Welcome to the World of Fast Morphing!

ANSYS CONVERGENCE 2013 REGIONAL CONFERENCES

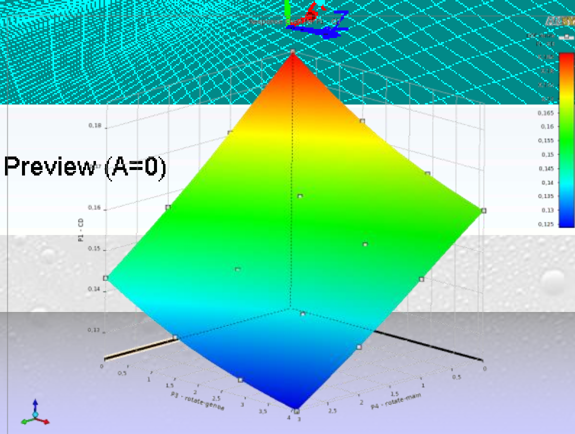
Motorbike Windshield (Bricomoto, MRA)



Sails Trim (Ignazio Maria Viola, University of Newcastle)



Morphing Preview (A=0)



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Exhaust manifold
Constrained Optimization
Adjoint Solver

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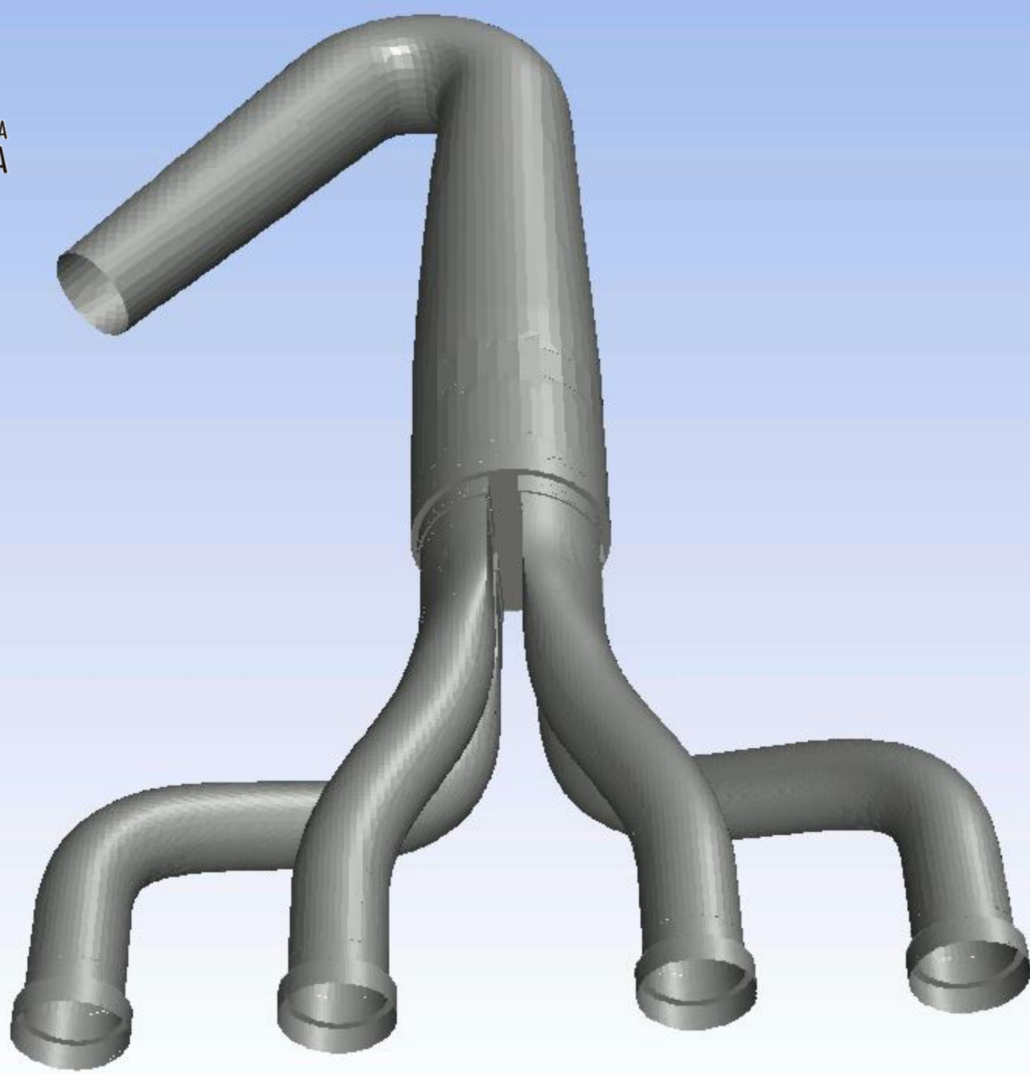
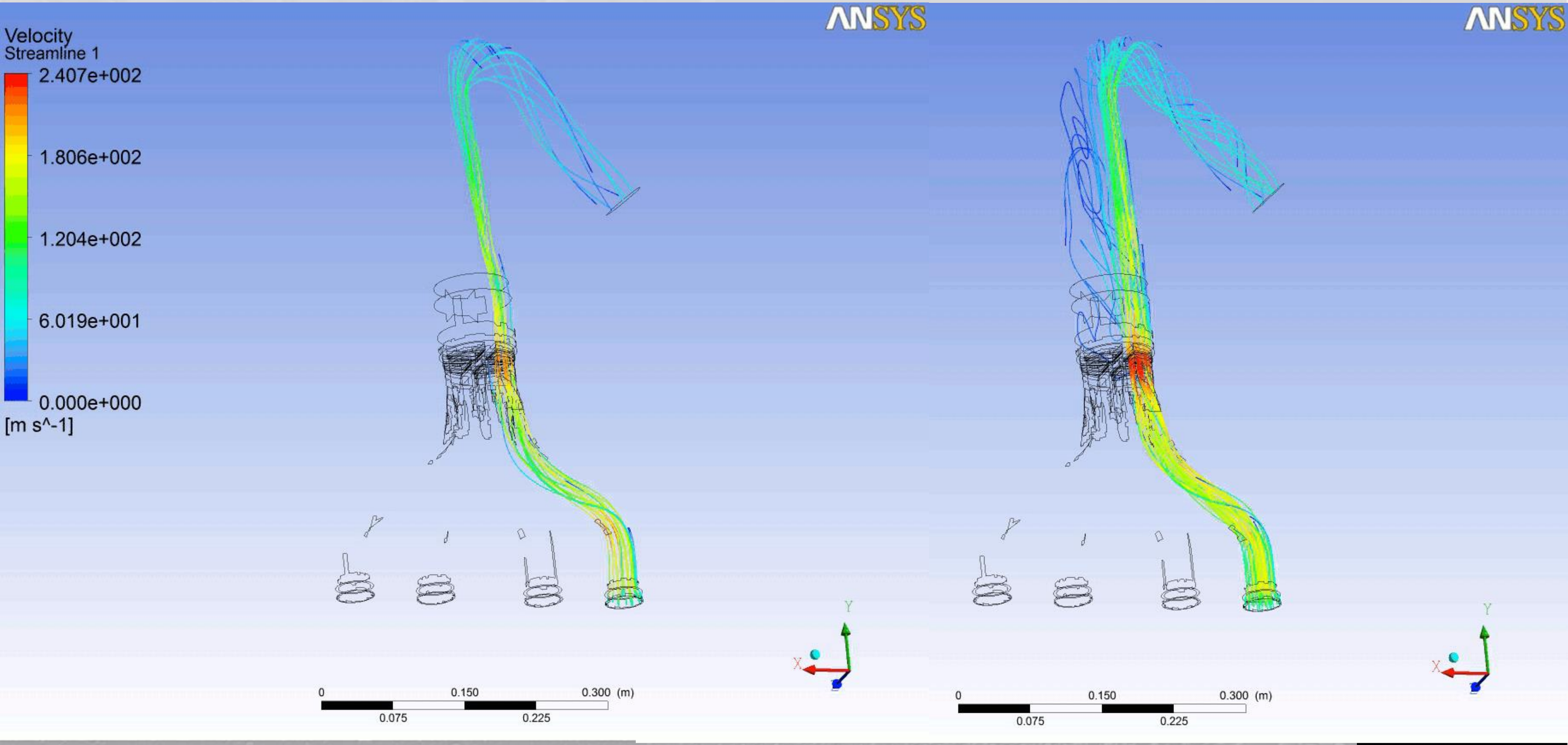


Name	P5 - Pipe1Curve1	P6 - Pipe2	P7 - Pipe4Curve1	P8 - Pipe3	P1 - PressureDrop1	P2 - PressureDrop2	P3 - PressureDrop3	P4 - PressureDrop4
					Pa	Pa	Pa	Pa
Current	4	4	4	4	12892	11366	13028	16619
DP 1	3	3	3	3	12882	11247	13487	16731
DP 2	2	2	2	2	12897	11546	13554	16911
DP 3	1	1	1	1	13403	11477	13920	17666
DP 4	0	0	0	0	13555	11750	13967	17718

Optimized vs. Original - Streamlines



Optimization of sweep angles (Piaggio Aero Industries)

PIAGGIO AERO

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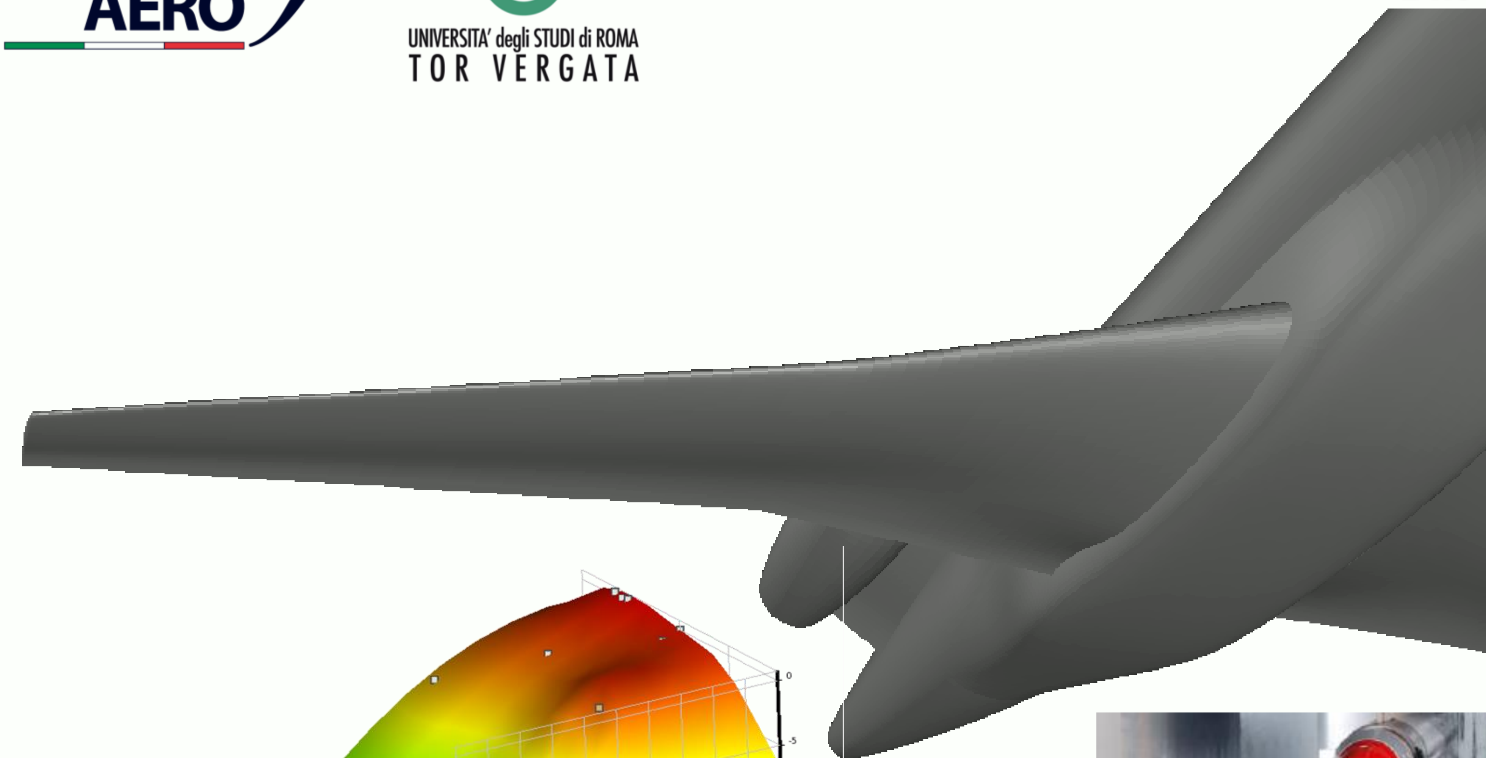
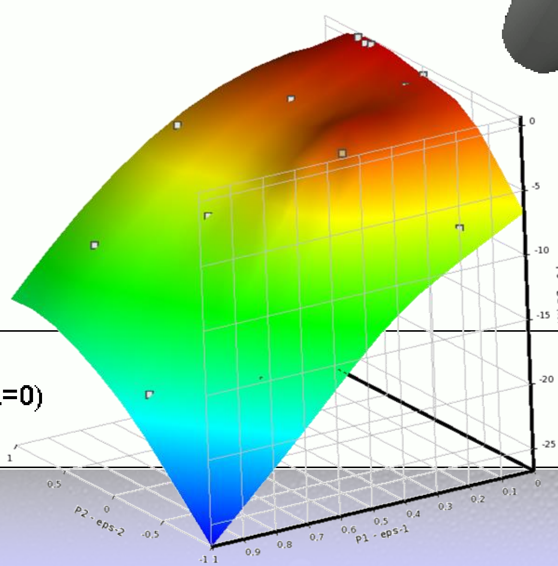
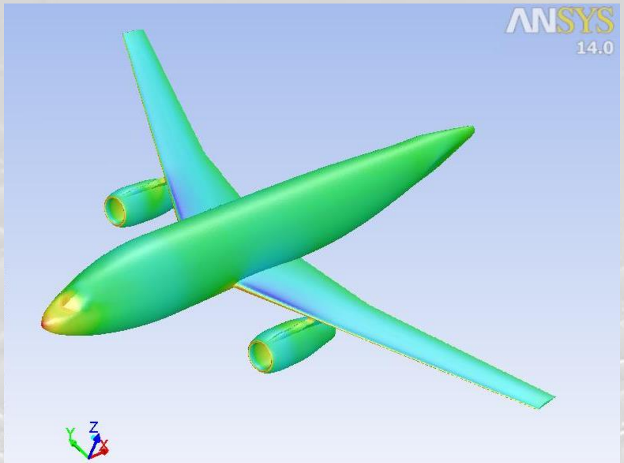
ANSYS 14.0

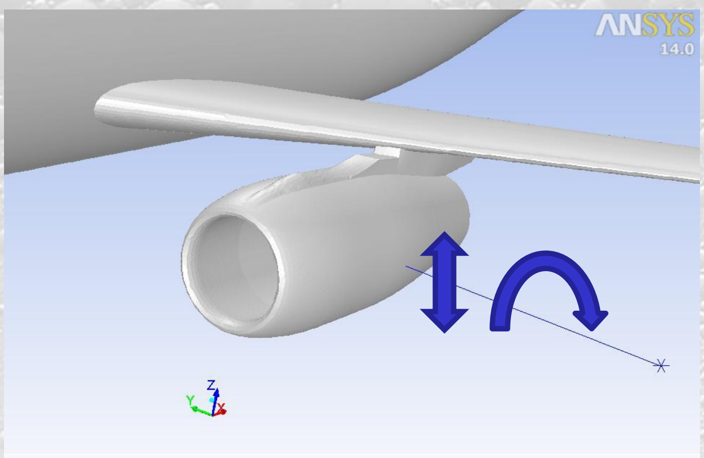


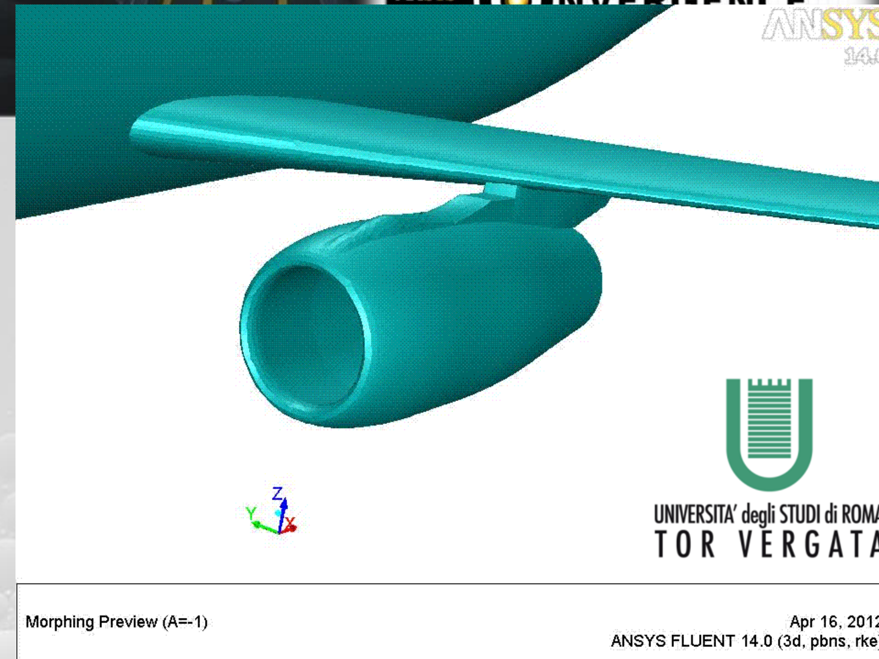


Morphing Preview (A=0)

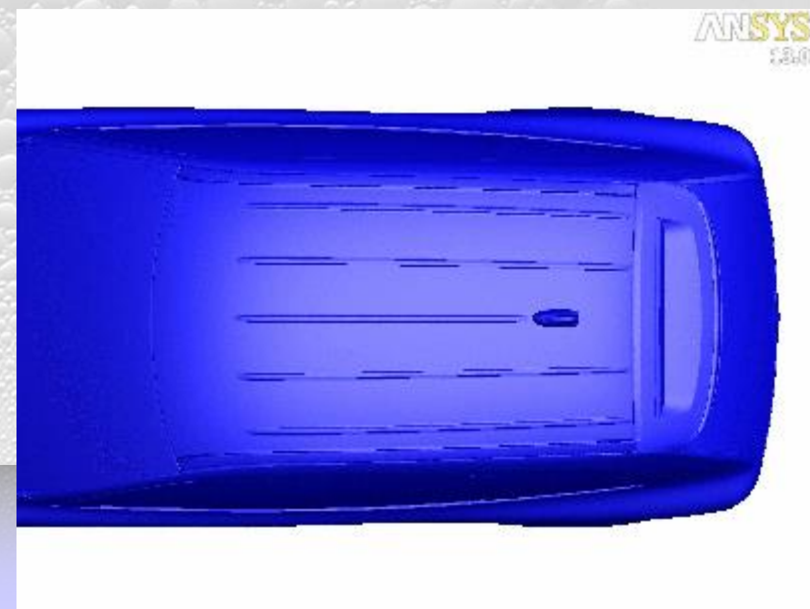
Optimization of nacelle (D'Appolonia)





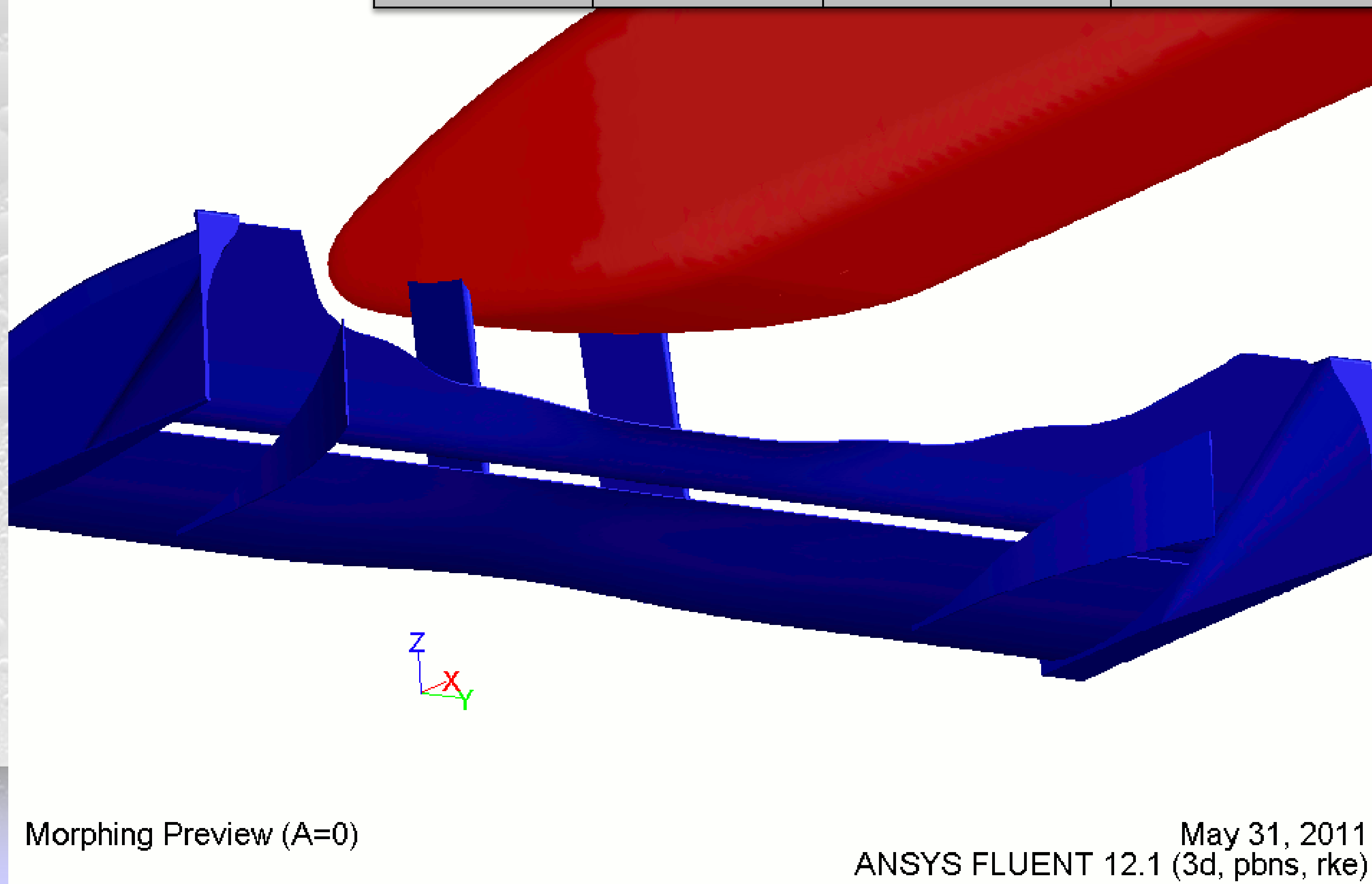


50:50:50 Project Volvo XC60 (Ansys, Intel, Volvo)

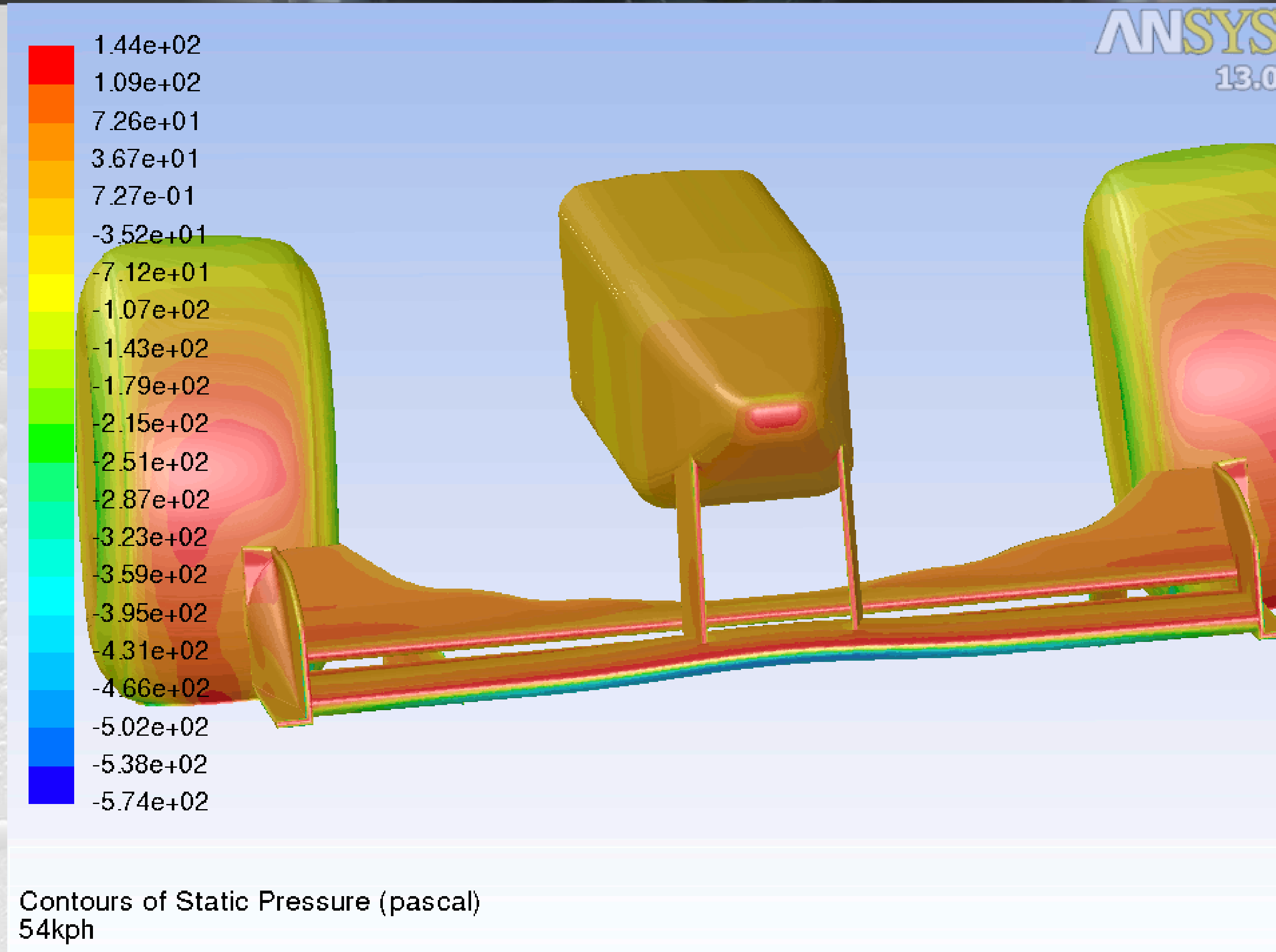


Aeroelastic Analysis of Formula 1 Front Wing

Mode	Disp(mm)	Max err(mm)	Max err (%)
1	7,19	1,61	22,39
2	7,19	0,86	12,00
3	6,98	0,85	12,15
4	6,90	0,66	9,50
5	6,85	0,19	2,76
2 Ways FSI	6,98	0,00	0,00



Aeroelastic Analysis of Formula 1 Front Wing



MORPH lab

LET'S PLAY TOGETHER!

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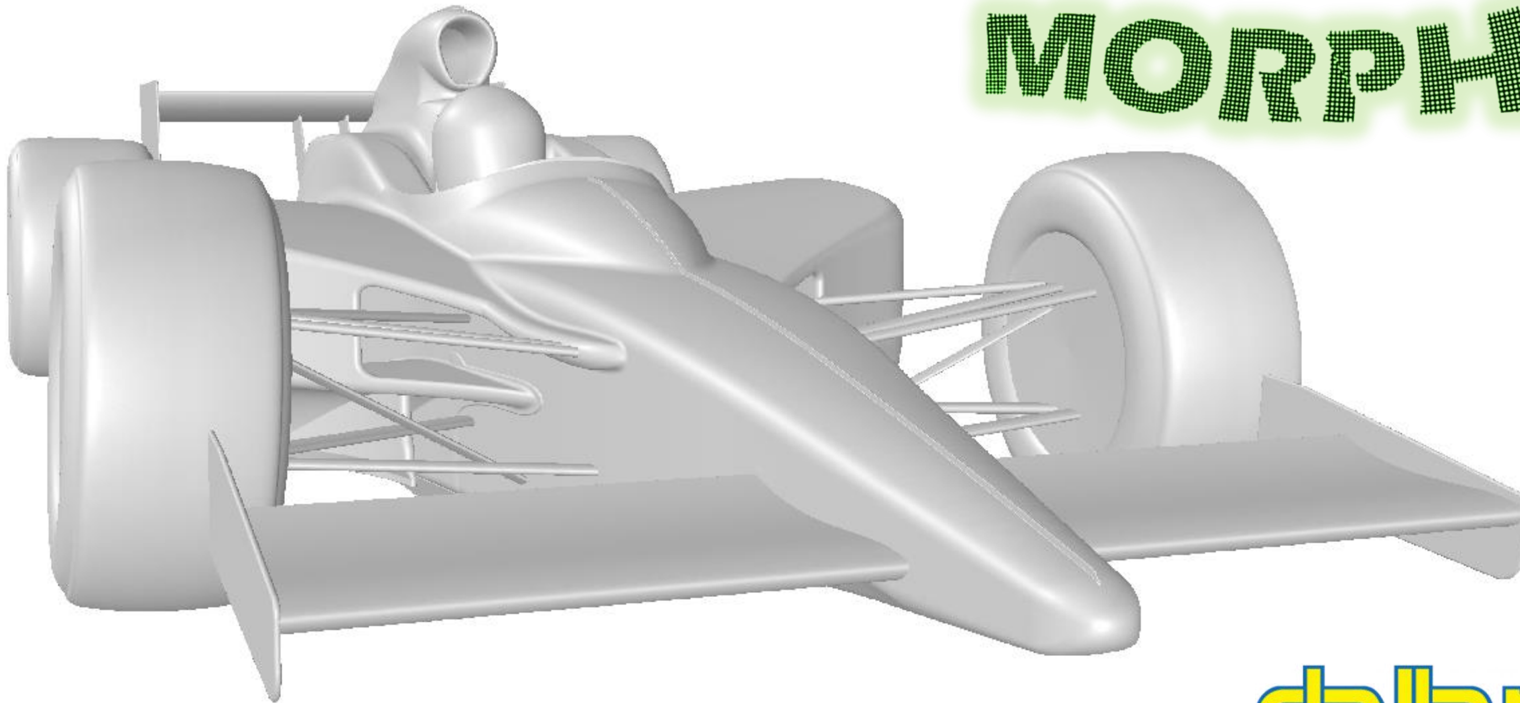
What is MorphLab?

Morph lab is the convergence point of academic research, industrial innovation, software and hardware development, where people, companies and developers can work together to push knowledge to a higher level.

Why MorphLab?

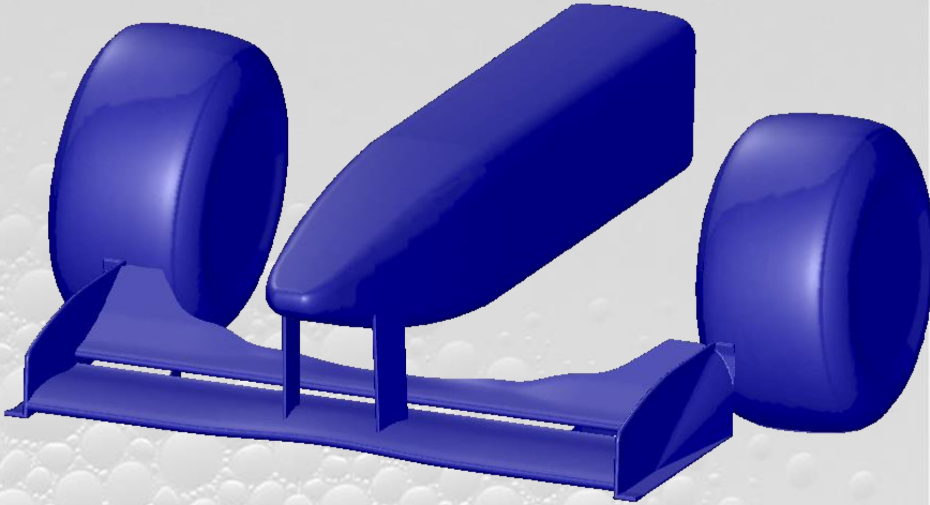
- **partners** can find fast solutions to specifical morph related industrial cases,
- **hardware** and **software** products can be tested and improved in demanding applications,
- **product developers** can advance their knowledge in the field of mesh morphing sharing data and workflows.



Generic Formula 1 Front End

Generic Formula 1 Front End

- Geometry provided by ANSYS:
  - STEP file
  - Tetrahedral mesh (880236 nodes)
  - Hexcore mesh (2497687 nodes)
  - Polyhedral mesh (3829310 nodes)



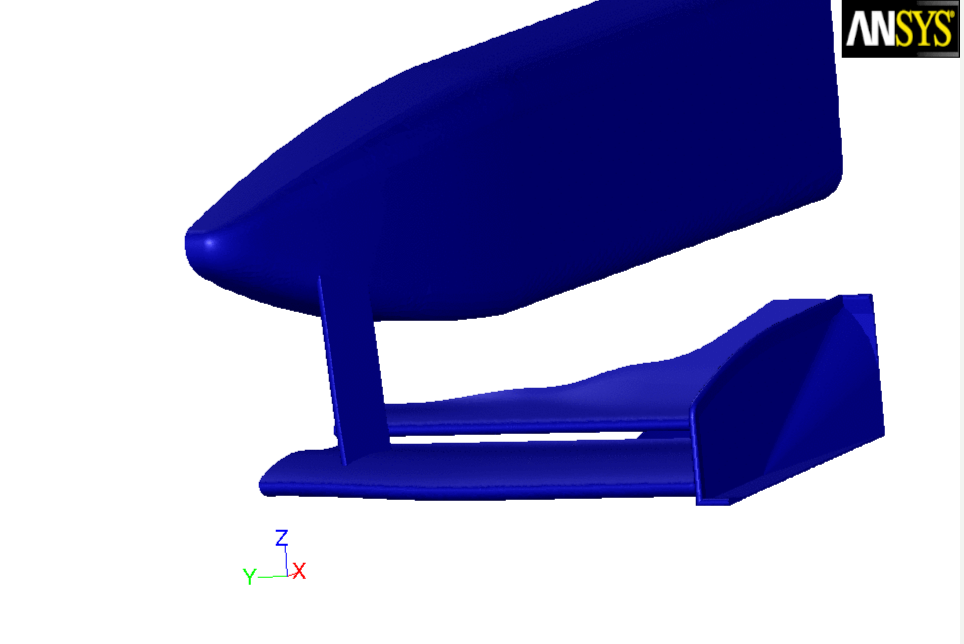
- 16 shape solutions investigated
- 240 CFD models (5 amplifications for 16 solutions for 3 baseline mesh) generated in serial in about 5 hours
- Only 3 meshes stored (tetra, hexcore, poly); the RBF is computed only once for the tetra
- 2 working days for the complete analysis!

Explored modifiers

1. Spanwise extension of the whole front wing (3 variations)
2. Rotation of the end plate of the front wing (about x and z axis)
3. Rigid movements of the flap (rotation, rigid translation in x and z)
4. Translation in z and x (two variations) of the whole front wing, for the x translation include also the vertical strut
5. Rotation of the whole front wing around the y axis
6. Coupling 4 & 5
7. Bending of the nose of the body (two variations)
8. Wing vane adjust (two variations)

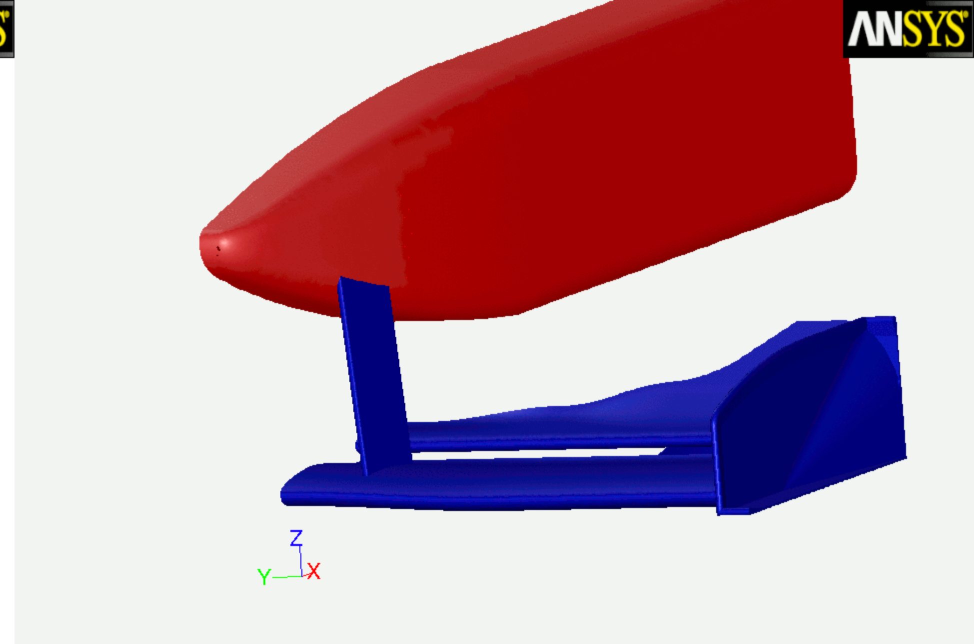
Summary (tet mesh case, serial)

Solution	Unit	Range	Solution Time (s)	Morphing Time (s)	Skeweness Range (5 values equal spaced; unreformed 0,8499)				
01-a	mm	0:-20	1	23	0,8499	0,8569	0,8638	0,9068	0,9457
01-b	mm	0:-20	1	21	0,8499	0,8499	0,8566	0,9089	0,9475
01-c	mm	0:-20	1	11	0,8499	0,8499	0,8499	0,9075	0,9607
02-a	deg	-7:7	1	11	0,9562	0,8499	0,8499	0,8606	0,9802
02-b	deg	-3:3	1	11	0,9935	0,8687	0,8499	0,8499	0,9929
03-a	deg	-5:5	40	78	0,9957	0,9165	0,8499	0,9323	0,9840
03-b	mm	-10:10	32	106	0,9999	0,9720	0,8499	0,9921	0,9998
03-c	mm	-4:10	32	92	0,9998	0,9946	0,8499	0,9715	0,9957
04-a	mm	-20:30	5	45	0,8583	0,8499	0,8518	0,9306	0,9987
04-b	mm	-20:20	5	47	0,9043	0,8499	0,8499	0,8535	0,9434
04-c	mm	-20:20	5	40	0,9044	0,8601	0,8499	0,8731	0,9451
05-a	mm	-2.5:2.5	6	50	0,9361	0,8499	0,8499	0,8515	0,9644
07-a	mm	-20:20	6	48	0,8499	0,8499	0,8499	0,8499	0,8499
07-b	deg	-2:2	6	51	0,8635	0,8536	0,8499	0,8504	0,8532
08-a	mm	-5:5	8	30	0,9859	0,9258	0,8499	0,8948	0,9746
08-b	mm	-10:10	8	33	0,8498	0,8498	0,8499	0,8500	0,8501



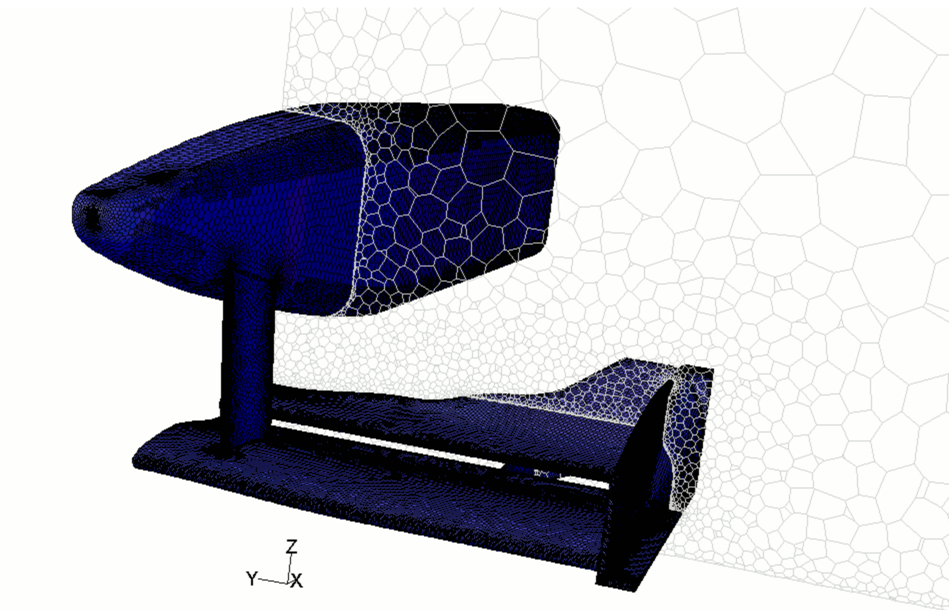
Morphing Preview (A1=-20, A2=-2)

Oct 24, 2010
ANSYS FLUENT 12.1 (3d, pbns, lam)

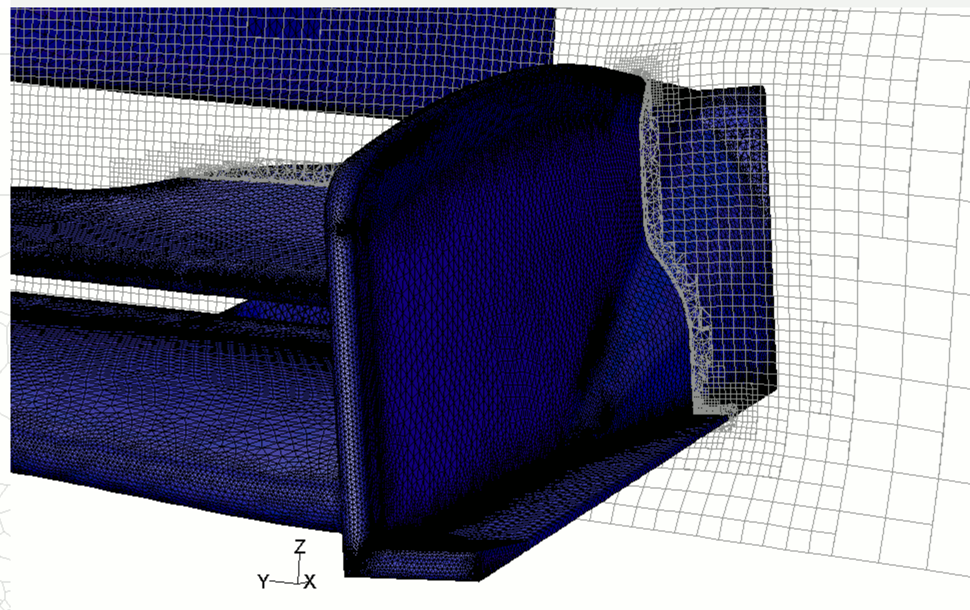


Morphing Preview (A=-20)

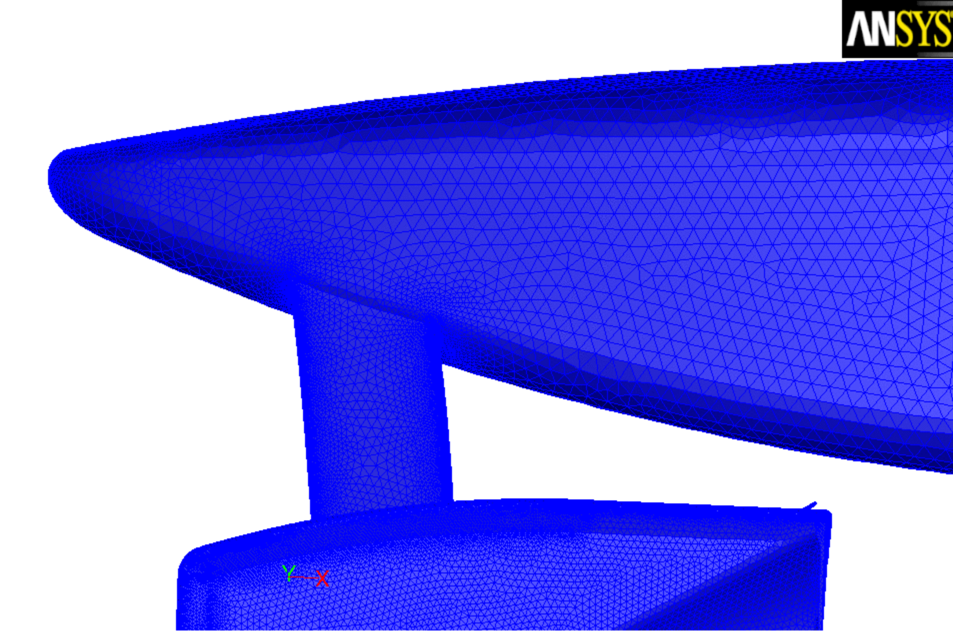
Oct 24, 2010
ANSYS FLUENT 12.1 (3d, pbns, lam)



Sol=sol-01-c, A=0
Surface Grid

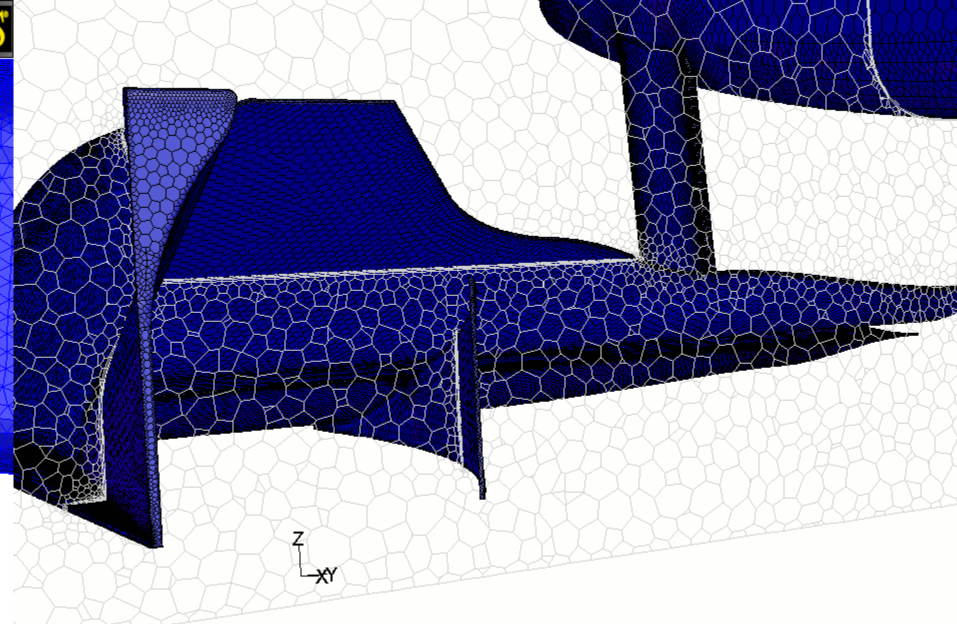


Sol=sol-02-a, A=-7
Surface Grid

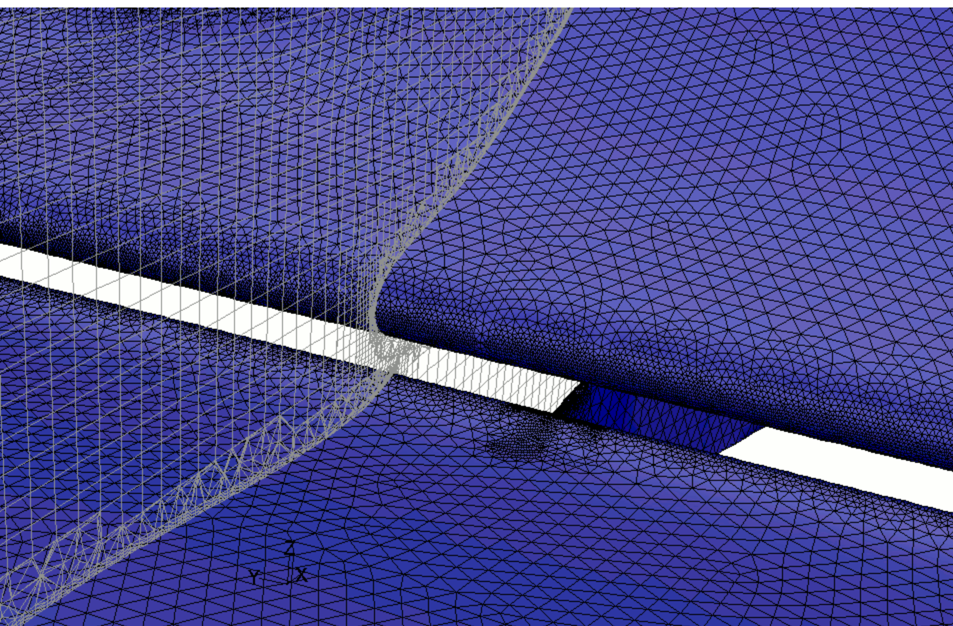


Morphing Preview (A=-20)

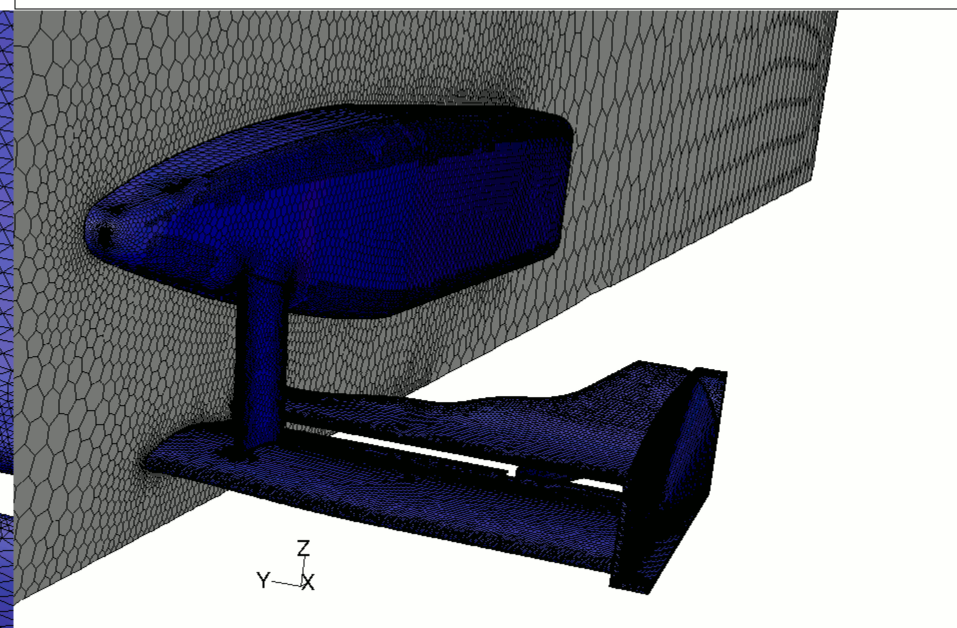
Oct 24, 2010
ANSYS FLUENT 12.1 (3d, pbns, lam)



Sol=sol-08-b, A=-10
Surface Grid



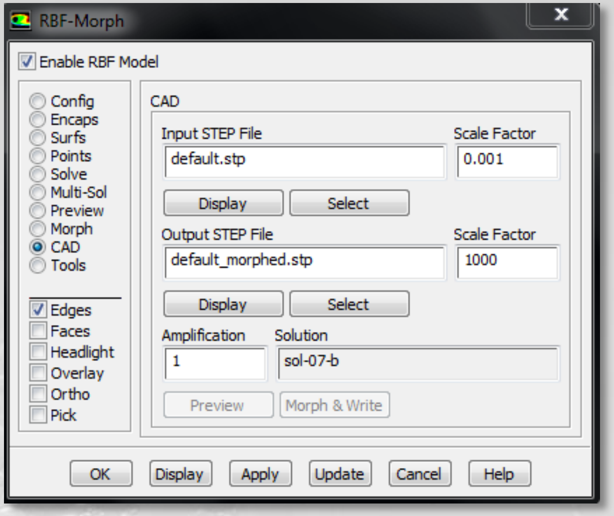
Sol=sol-03-a, A=-5
Surface Grid

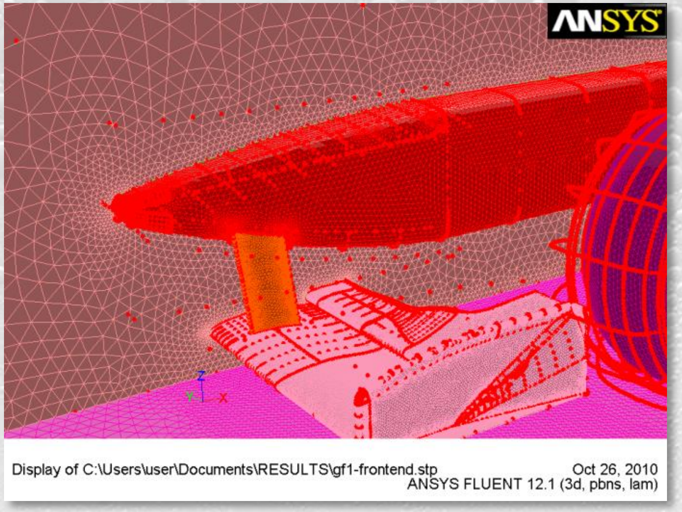


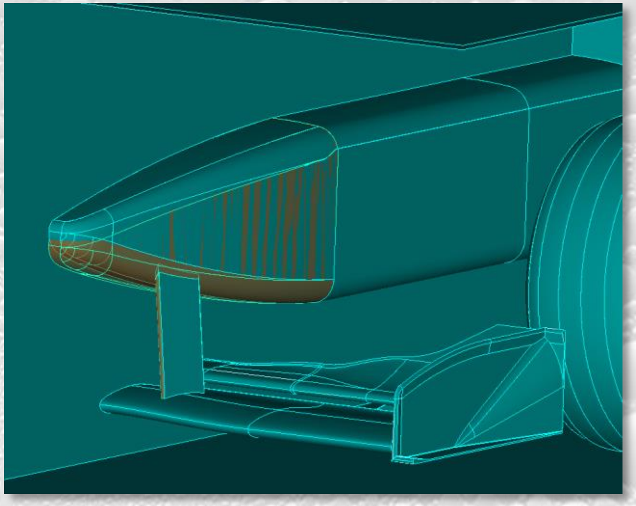
Sol=sol-07-a, A=-20
Surface Grid

Importing in the CAD the new design

- Solution 07-b with ampli = 1 has to be reversed (nose rotation 1 deg)
- STEP file of original shape is loaded (points overlap within Fluent GUI)
- Morphed STEP file is generated







Conclusions

- A **shape parametric** CFD model can be defined using ANSYS Fluent and *RBF Morph*.
- Such **parametric CFD model** can be easily coupled with preferred optimization tools to steer the solution to an **optimal design** that can be imported in the preferred **CAD** platform (using **STEP**)
- Proposed approach **dramatically** reduces the man time required for set-up widening the CFD calculation capability
- ***M.E. Biancolini***, *Mesh morphing and smoothing by means of Radial Basis Functions (RBF): a practical example using Fluent and RBF Morph* in Handbook of Research on Computational Science and Engineering: Theory and Practice (http://www.cse-book.com/).

RBF Morph benchmarking for an icing application

Based on NASA Lewice 2.0 validation results shapes

Corrado Groth

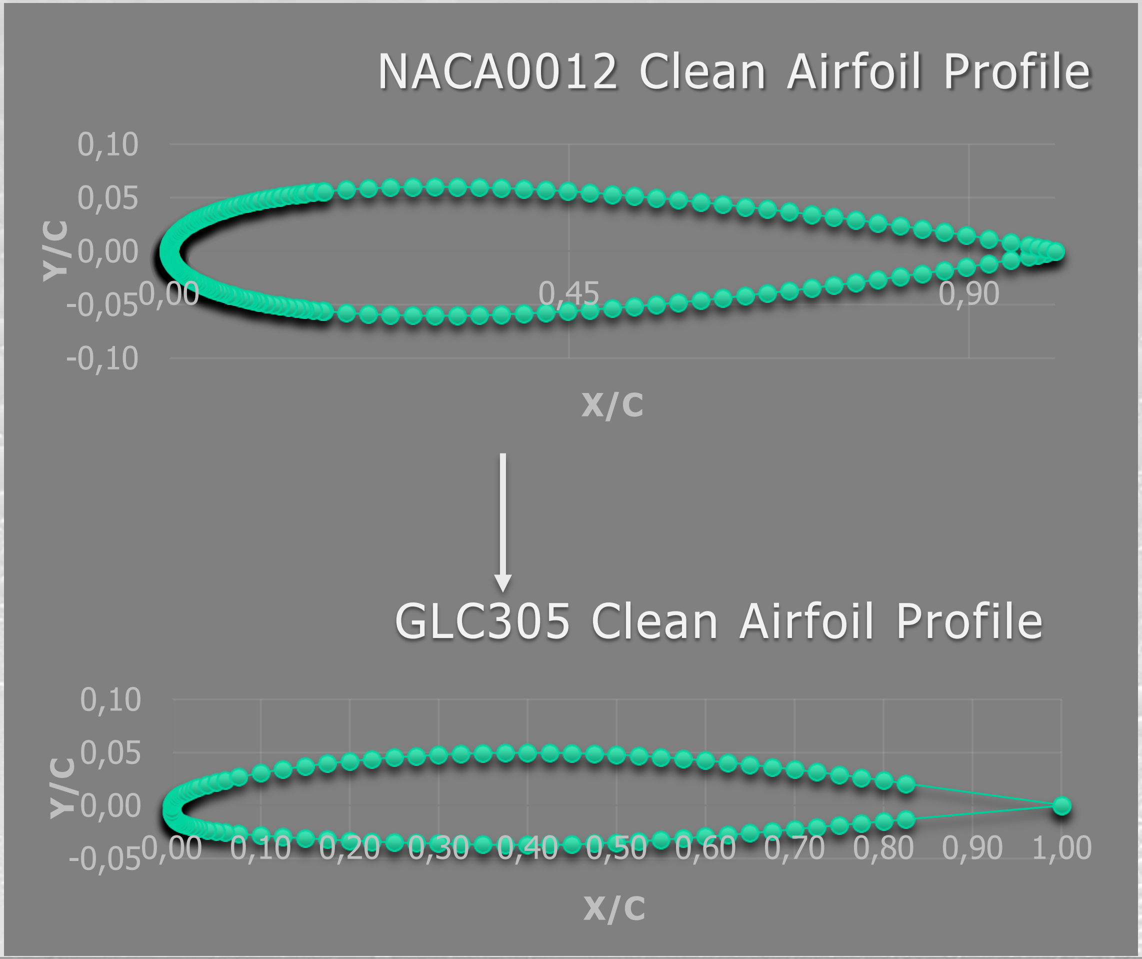
Marco Evangelos Biancolini

Tor Vergata

Feasibility study

- The method has been implemented both in 3D and then in 2D
- MathCAD tool is used to preprocess data and generate desired ice accretion profile (2D and 3D)
- All the tasks of this simplified workflow are conducted using standard commands of Fluent and RBF Morph
- Points panel is used to feed the morpher with ice profile data
- Capability of mesh morpher is validated using NASA Lewice 2.0 validation manual shapes

Wing profile morphing

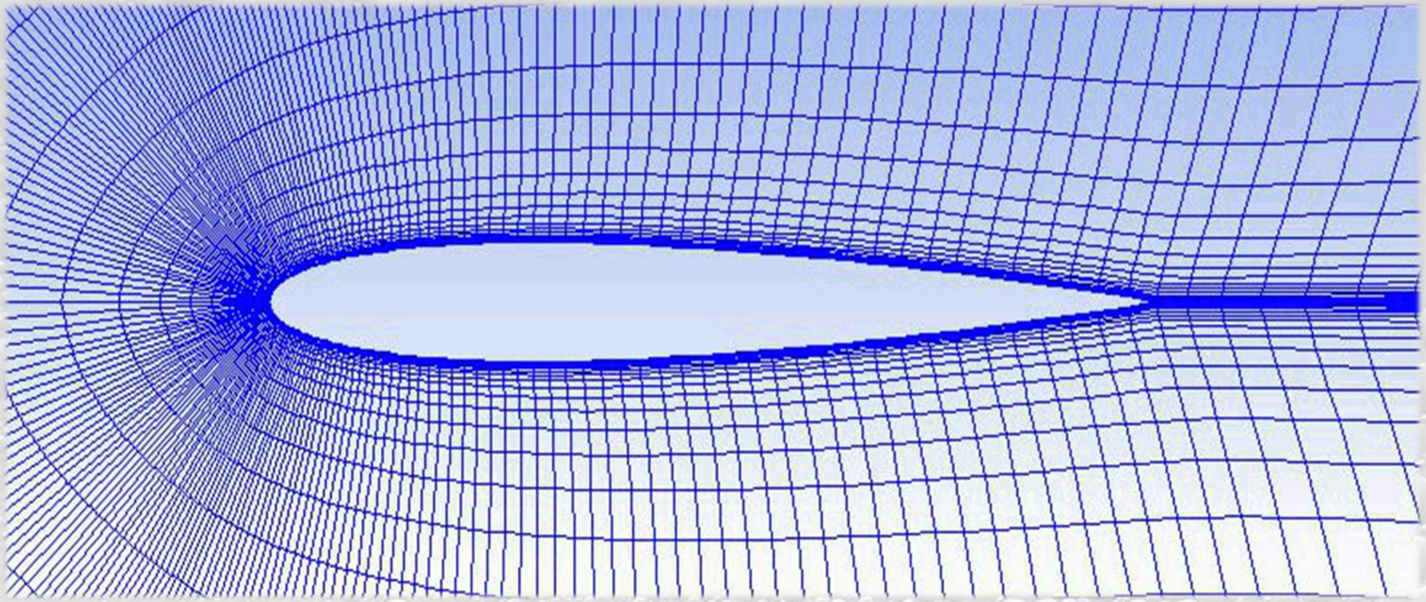


Wing models used for the benchmark:

- NACA0012
- GLC305

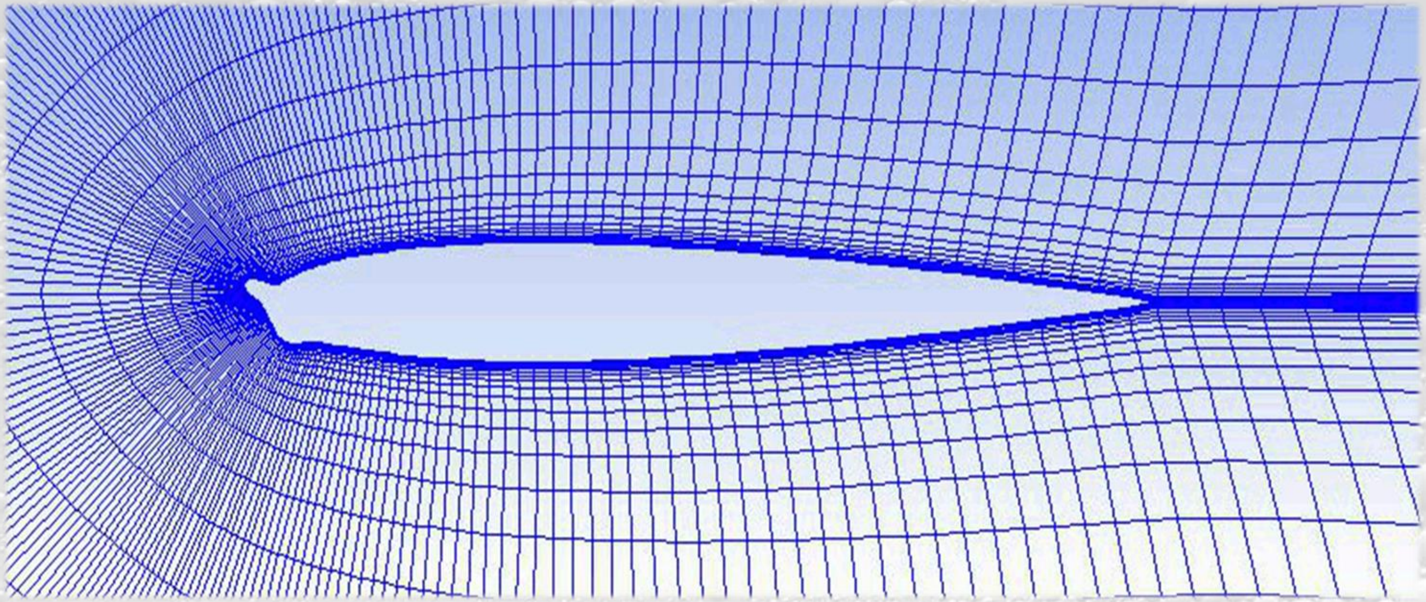
GLC305 profile was obtained morphing the NACA0012 shape

Wing profile morphing

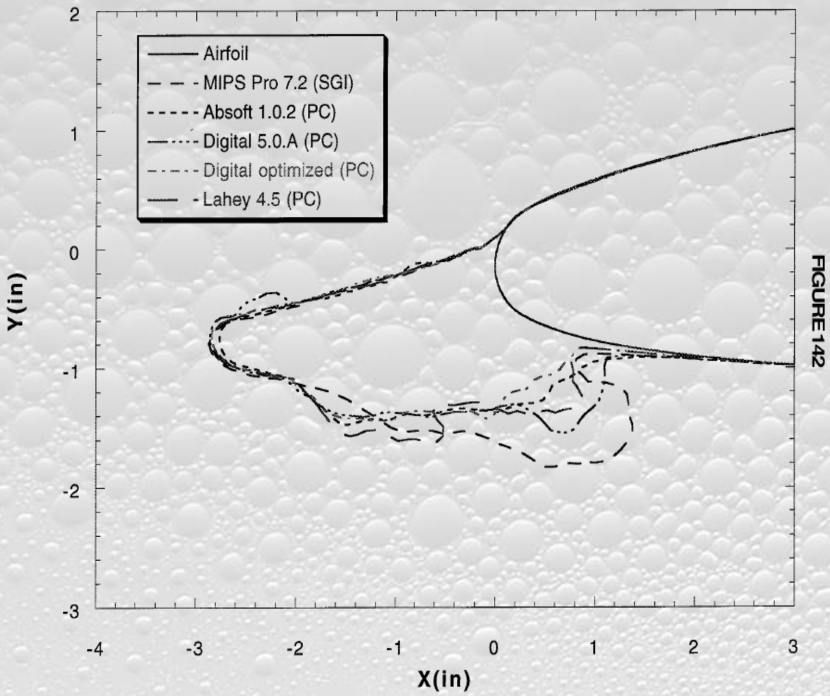


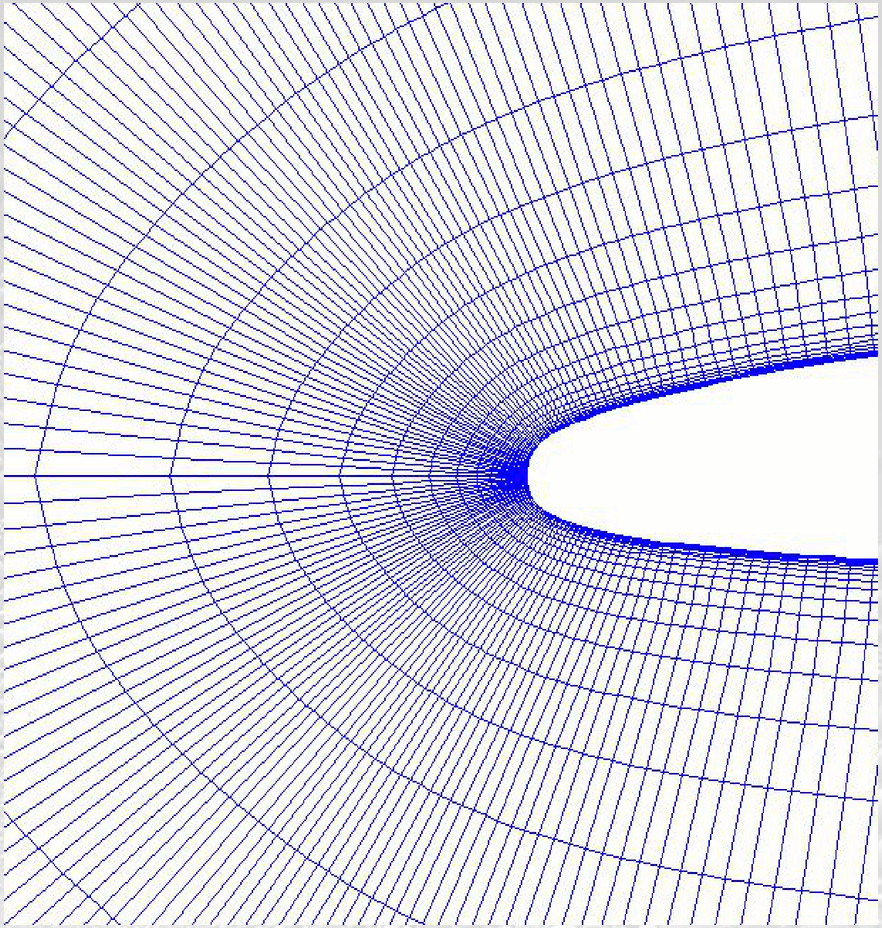
Ice accretion morphing

- All the ice shapes were taken from Nasa Lewice 2.0 validation results manual, picking the most challenging ones.
- Ice accretion has been assumed linear, allowing for an in-flight simulation during the ice-build up process.

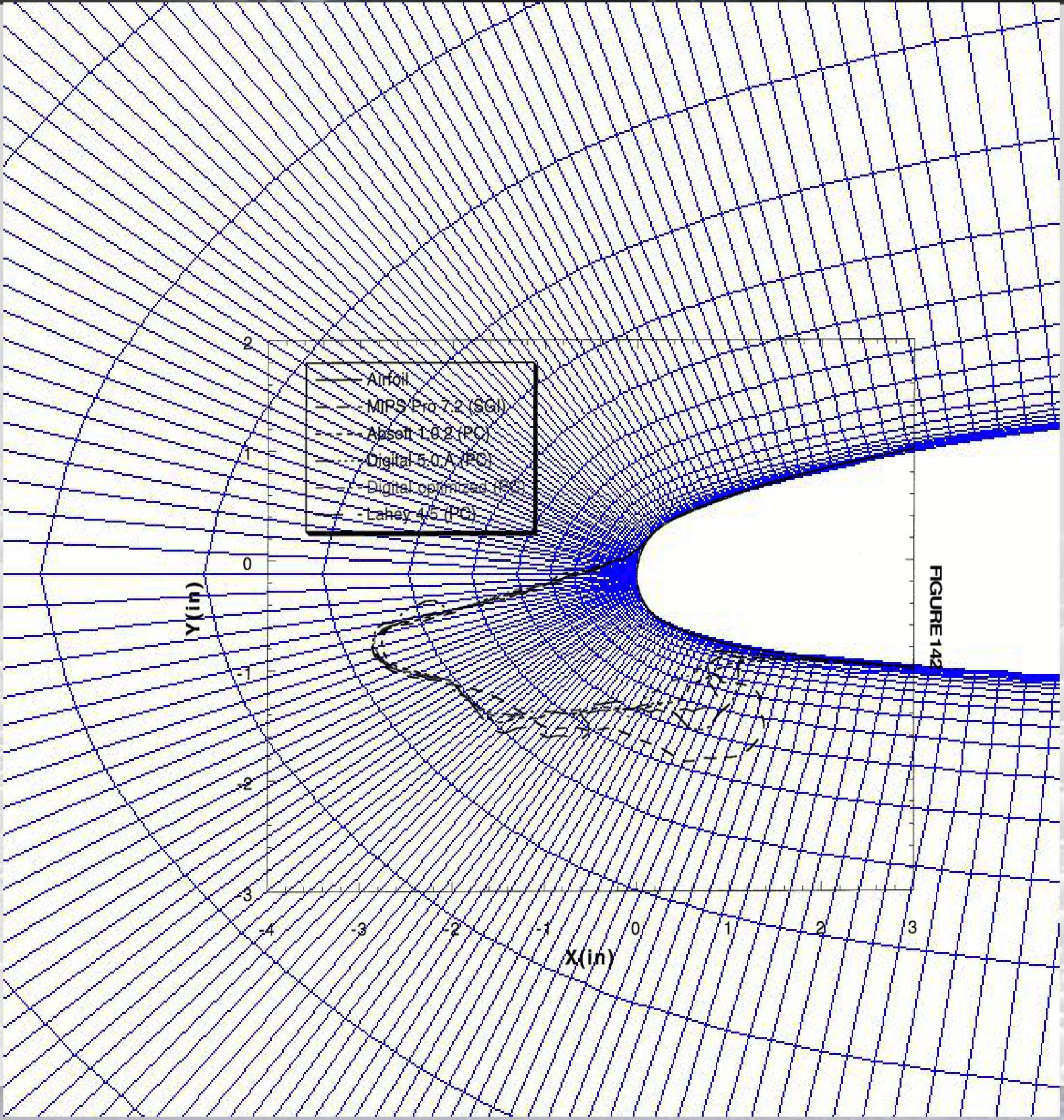


Ice accretion morphing

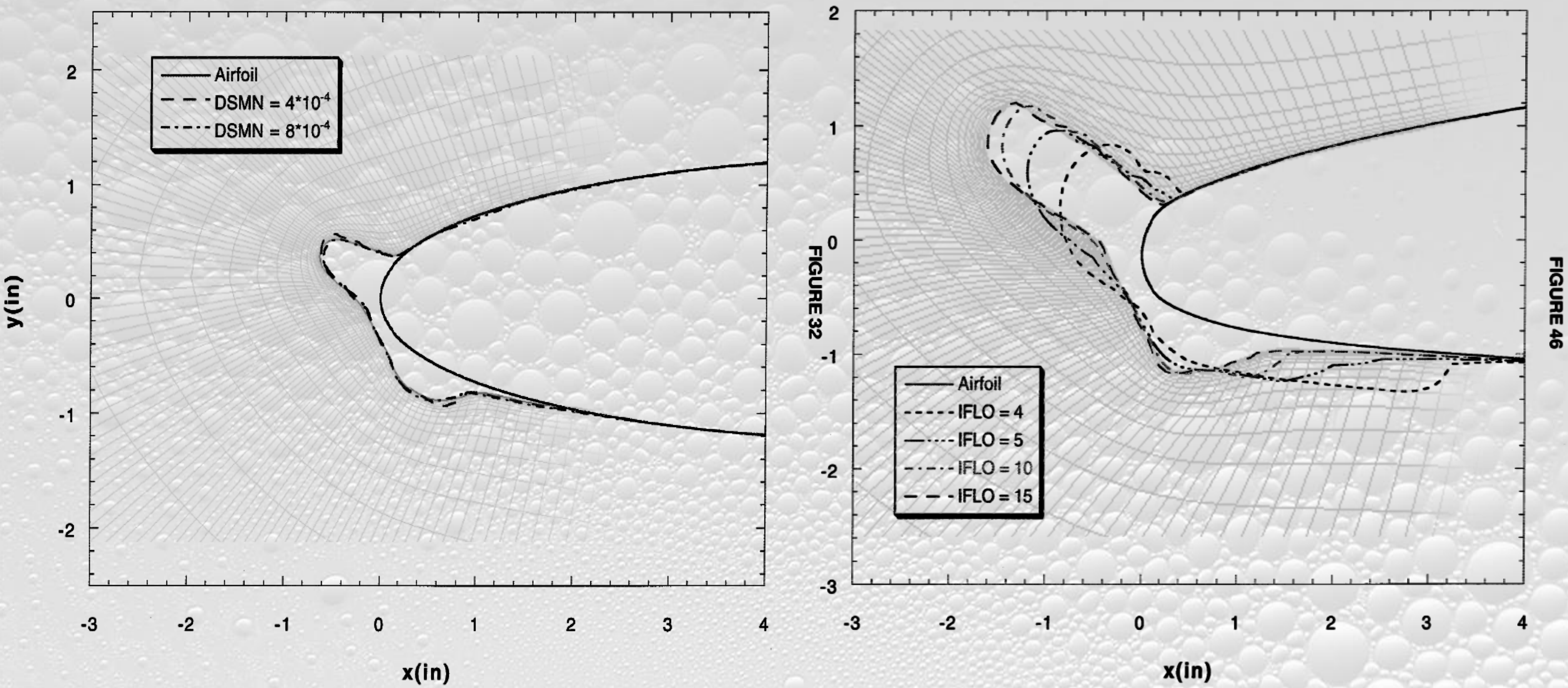




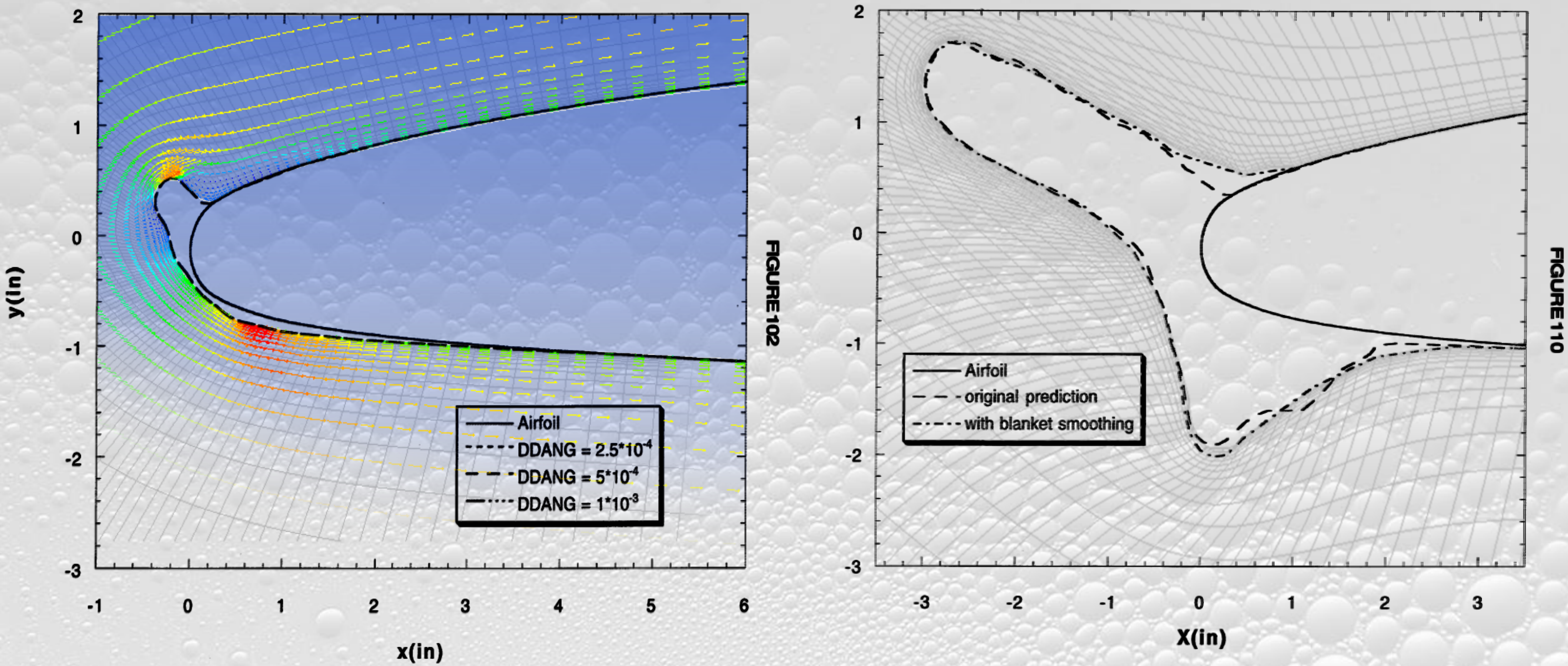
Ice accretion morphing



Ice accretion morphing

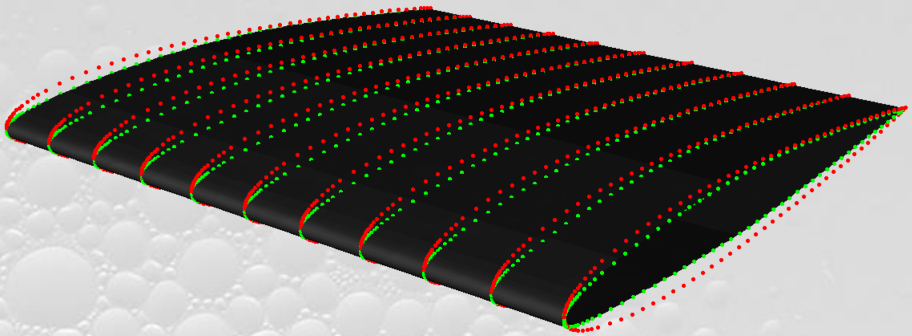


Ice accretion morphing



3D accretion morphing

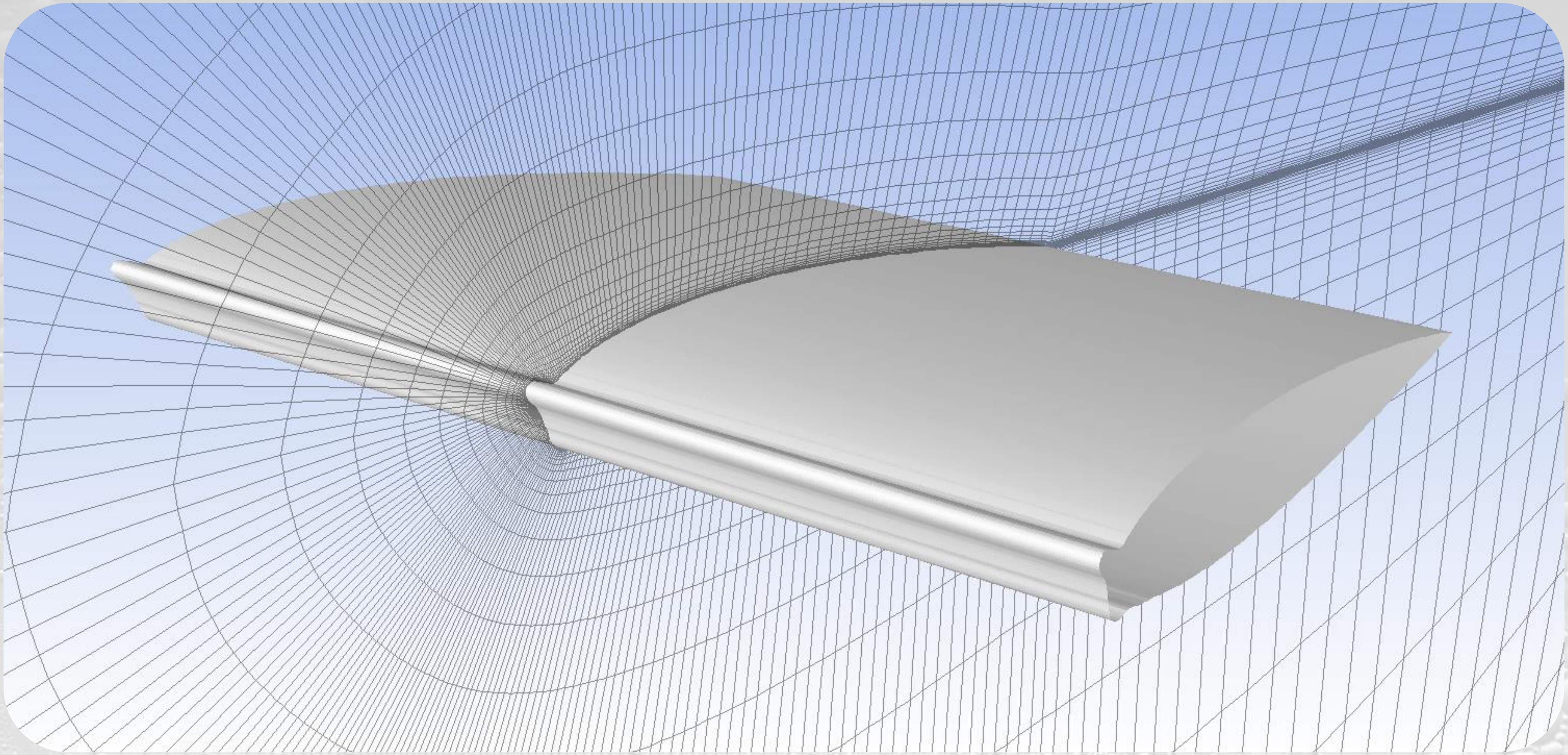
Also for the 3D accretion benchmark the GLC 305 clean wing was obtained morphing the NACA0012 profile.



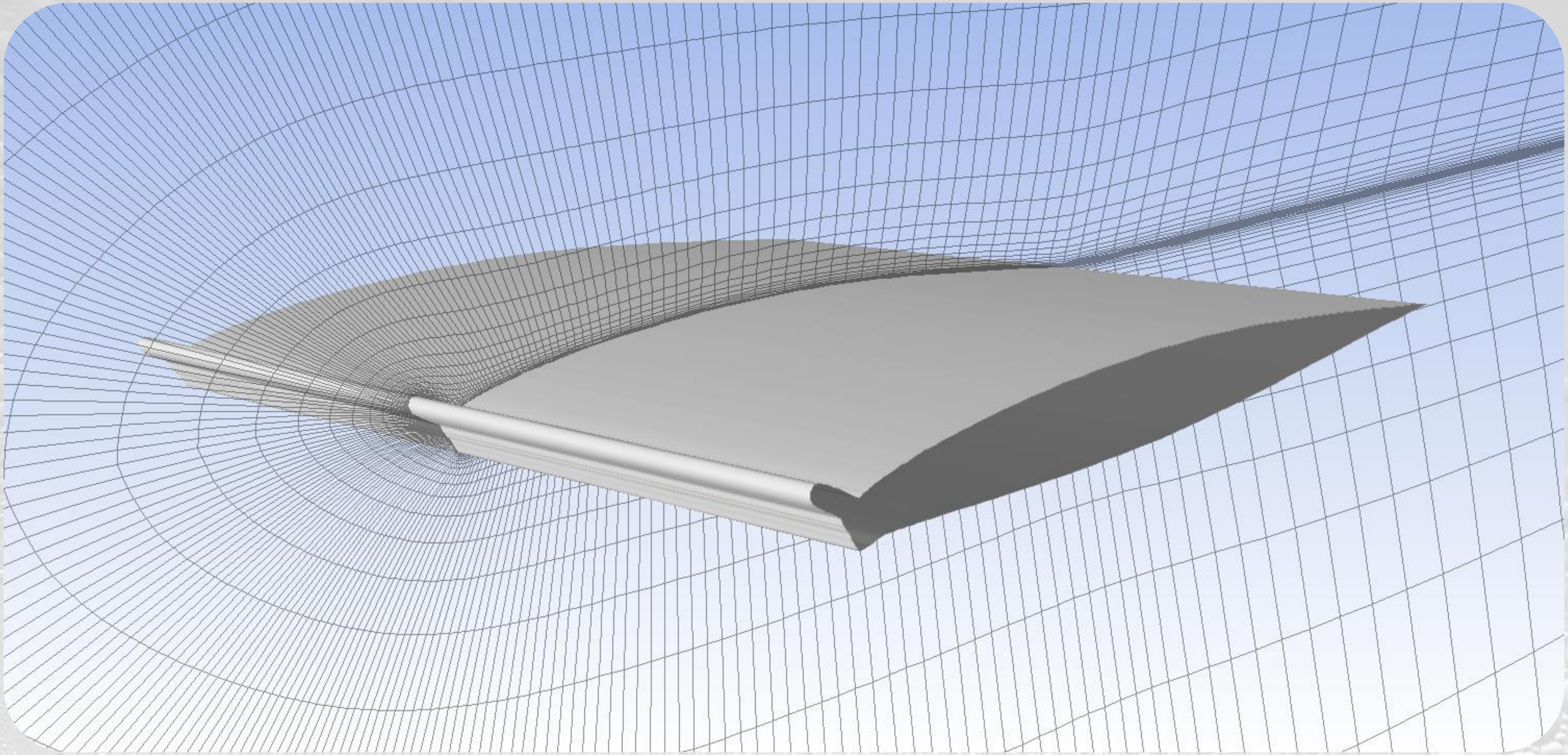
3D accretion was tested simulating both an even and a variable profile along the span

Accretion was assumed linear in the 3D case too.

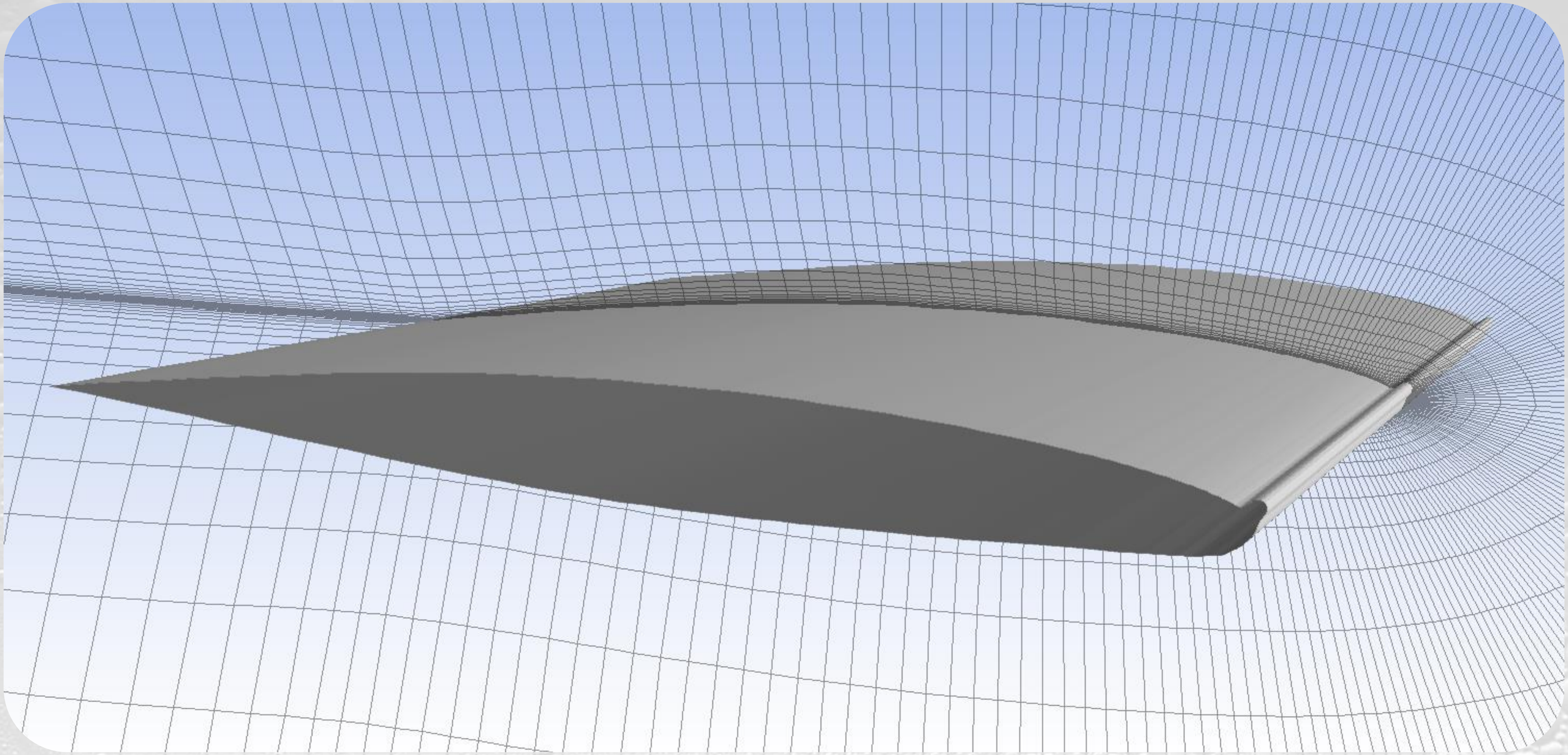
3D accretion morphing



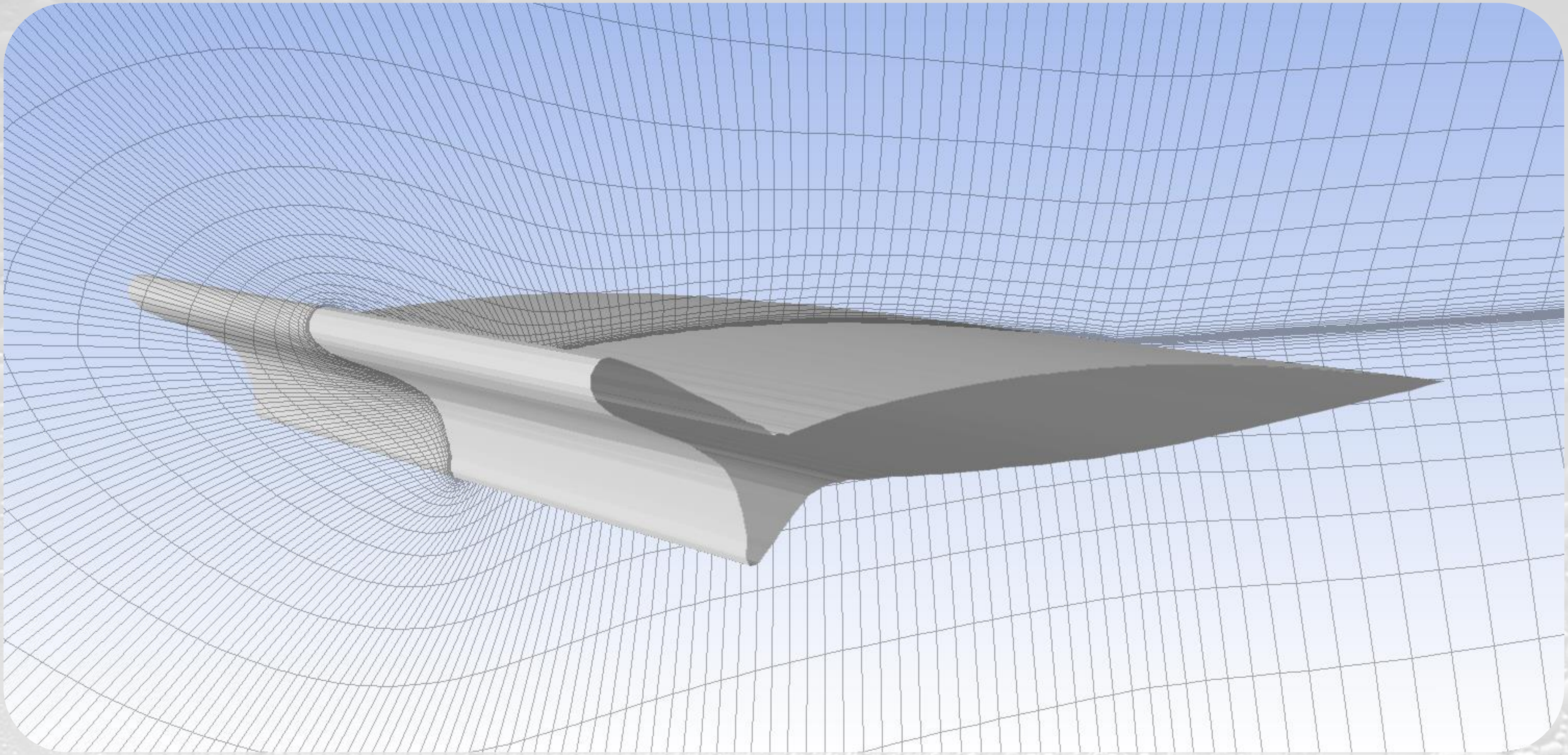
3D accretion morphing



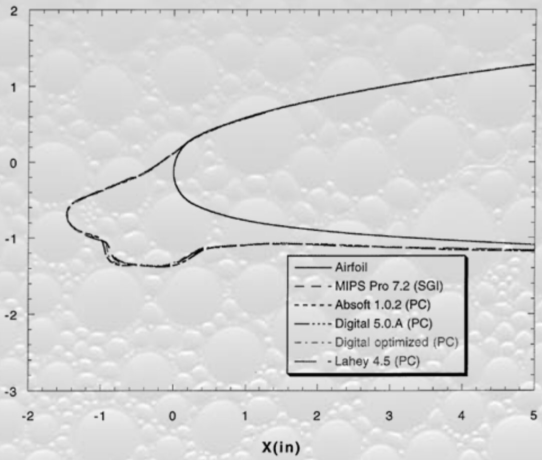
3D accretion morphing



3D accretion morphing



3D accretion morphing

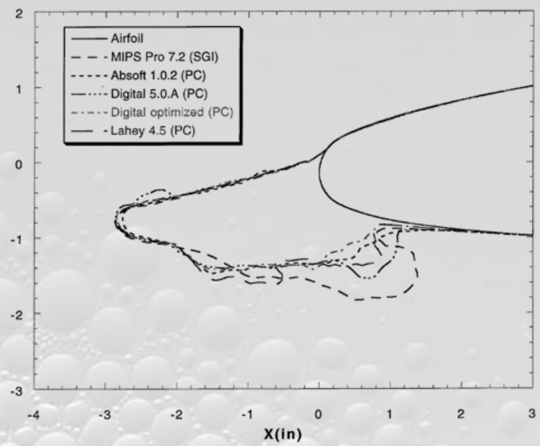


Shape A

Span 1

Shape B

Span 0



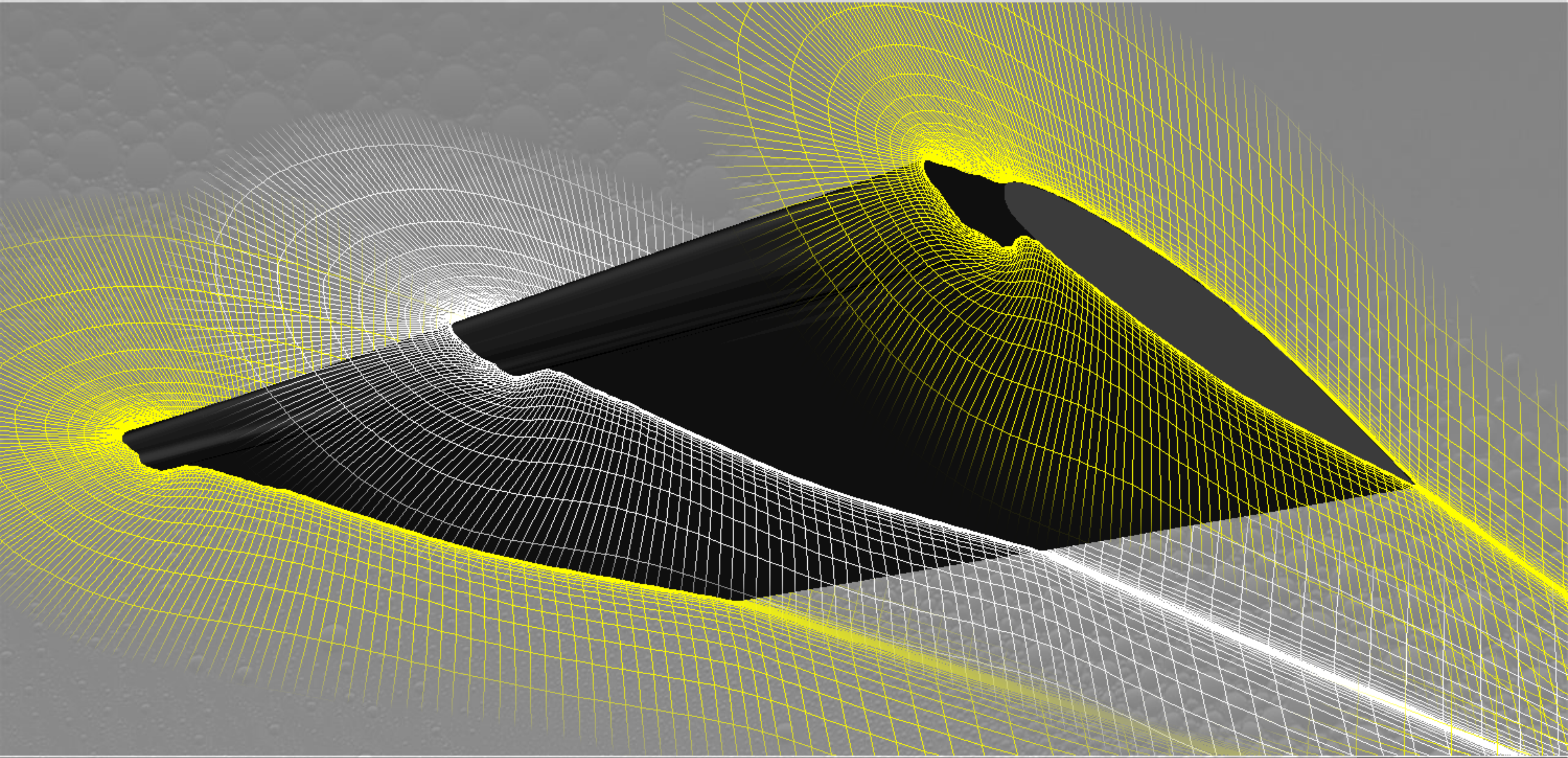
Variable accretion along the span was achieved imposing two different ice shapes at the wing extremities.

For a generic node C at span S the displacement was imposed as

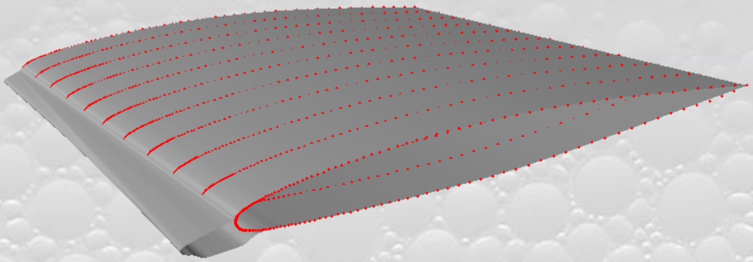
$$C = A \cdot (S) + B \cdot (1-S)$$

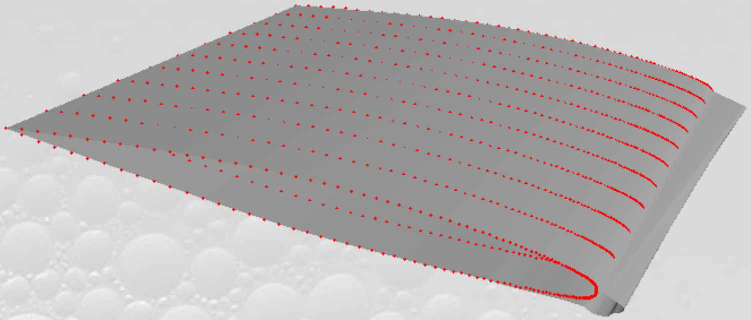
Where A and B are the displacements of homologous nodes for shapes A and B

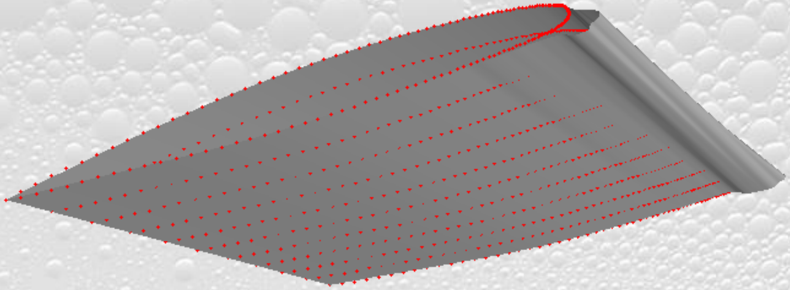
3D accretion morphing

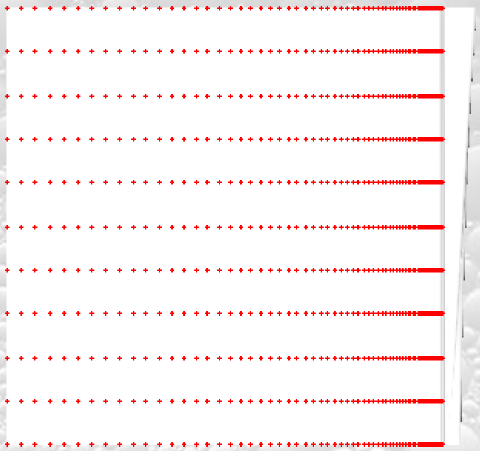


3D accretion morphing





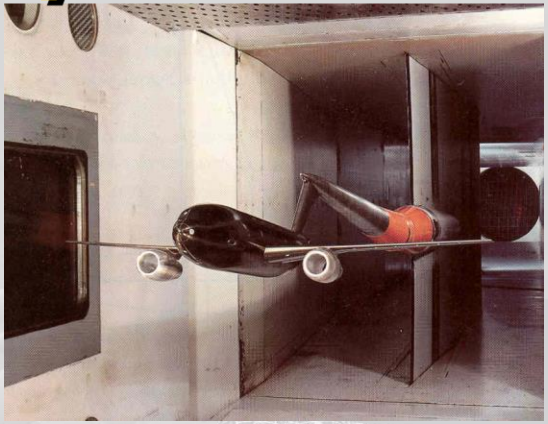




Conclusions

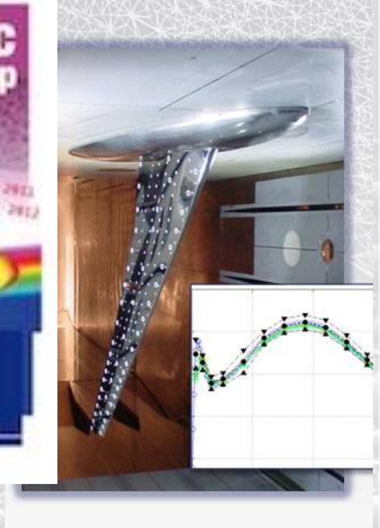
- Mesh morphing capability for ice profile representation has been demonstrated (2D and 3D).
- Quality is very good even for most challenging shapes, y+ values is preserved after morphing.
- The workflow can be easily automated without the need of MathCAD (using Fluent UDM + UDF)
- RBF Morph is capable to fit very large RBF in a reasonable time (100.000 points in less than 5 minutes) so large models can be handled using the same tools

Fluid Structure Interaction by modal superposition



- Research partnership (since 2009) between Piaggio Aero Industries & University of Rome Tor Vergata addressed to the solution of the aeroelastic problem using mesh morphing.
- Investigated aircraft geometries:

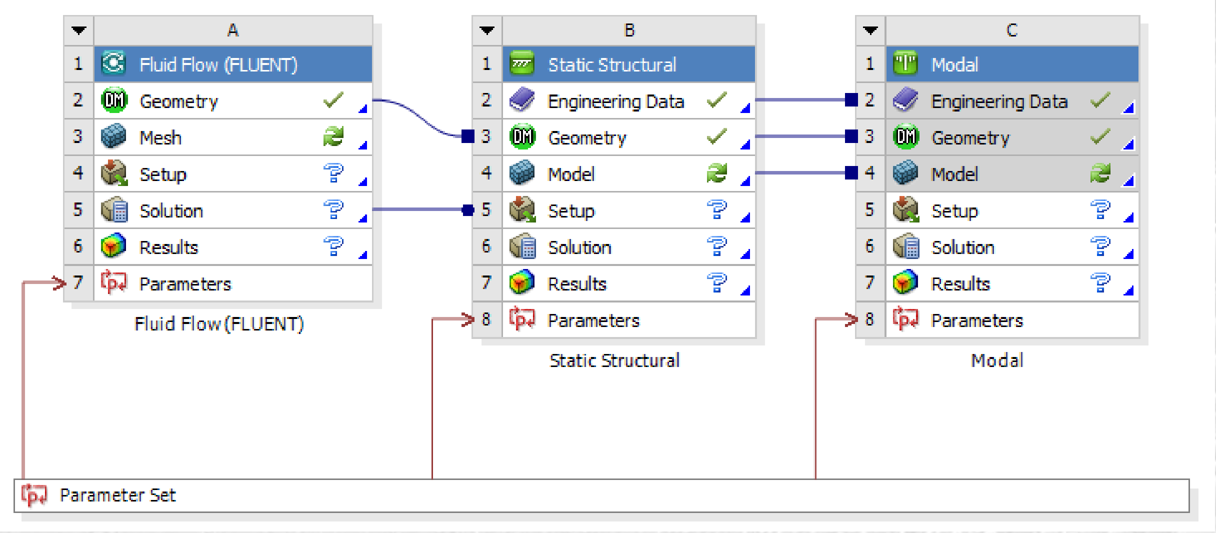
1. Wind tunnel model of a Piaggio business class aircraft in complete configuration.
2. Reference model of 2nd Drag Prediction workshop : DLR-F6 with nacelle.
3. Reference geometry of Aeroelastic Prediction Workshop: HIRENASD



Proposed workflow

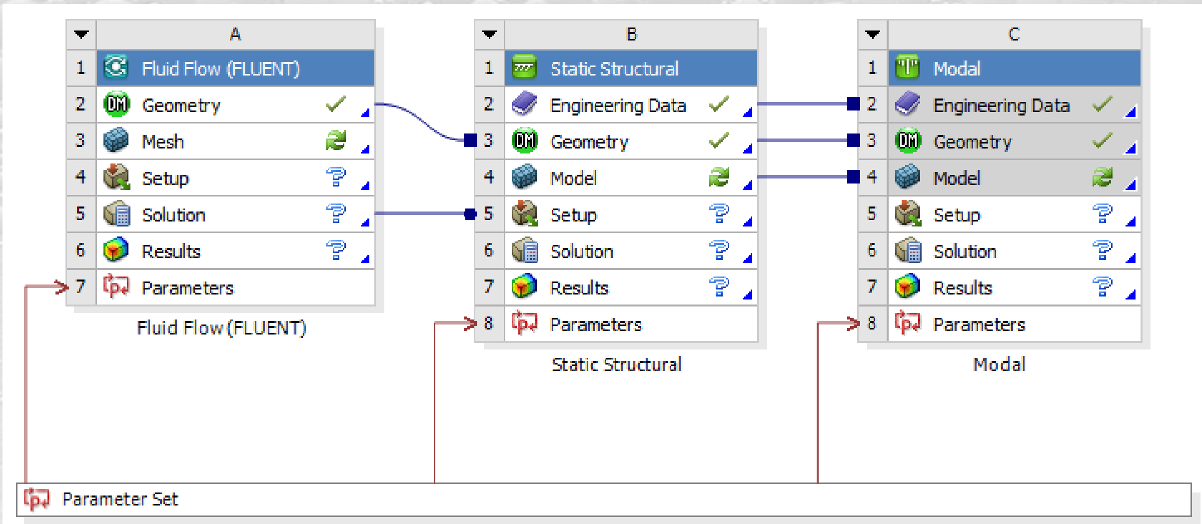
- Modal basis is computed using FEM solver
- Modes are imported into CFD model using RBF Morph
- Modal basis is validated using as reference FEM results with mapped CFD pressure

- **CFD Model + Modal Basis = Flexible CFD Model**



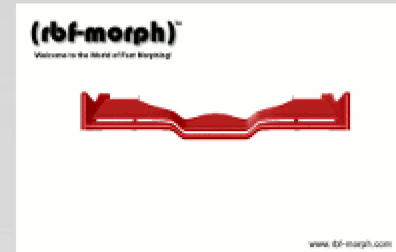
Proposed workflow

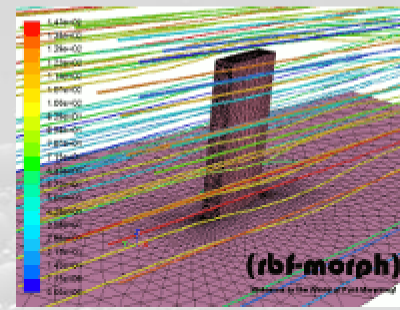
- CFD Model + Modal Basis = Flexible CFD Model
- Flexible CFD model allows to do a steady aeroelastic run at the same cost of a rigid one
- Flexible CFD model can be used for transient FSI
- Actual modal coordinates can be linked to FEM for stress recovery

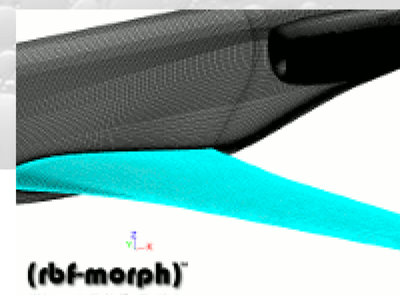


Key RBF Morph features for modal FSI

- Radial Basis Function Mesh Morphing provides excellent quality of morphed meshes.
- Fast solver of RBF Morph allows to deal with very large problems even for FSI
- Modal Forces are integrated within Fluent over the CFD surface mesh with actual pressure data
- FSI commands to fast update the mesh using current modal coordinates (steady & transient)







```
(define (modal-q-update-static)
;; calculate modal forces
(set! modal-forces (rbf-fmorph-forces '("front_wing_flap" ... "lin")))
;; update q = F / k
(set! modal-q (map / modal-forces modal-k))
;; update mesh
(rbf-fmorph (list (list "mode1-new" (list-ref modal-q 0)) ...)))
)
```

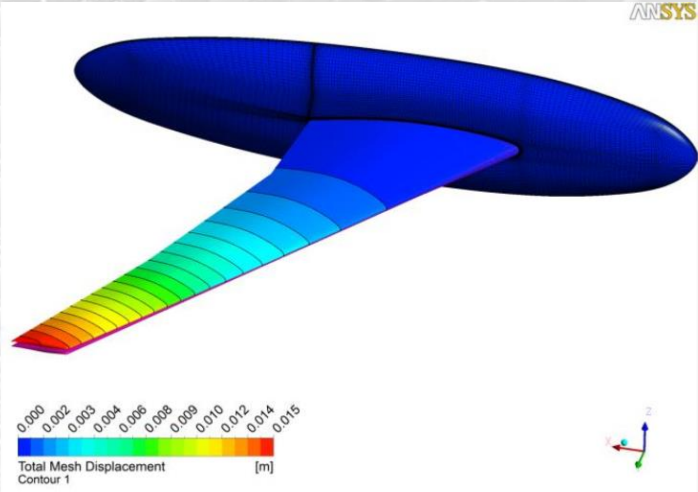
Modal basis validation

- Before trust the modal results the basis has to be validated with respect to full coupling and/or mapping (mm)

Mode	F1 Front Wing	DLR-F6	HIRENASD	Piaggio
1	7,19	4,97	15,259	4,657
2	7,19	4,797	14,183	4,412
3	6,98	4,75	14,184	4,423
4	6,90	4,76	14,257	4,448
5	6,85	4,79	14,257	4,399
6	*	4,81	14,257	4,431
Mapping	6,87	4,81	14,444	4,596

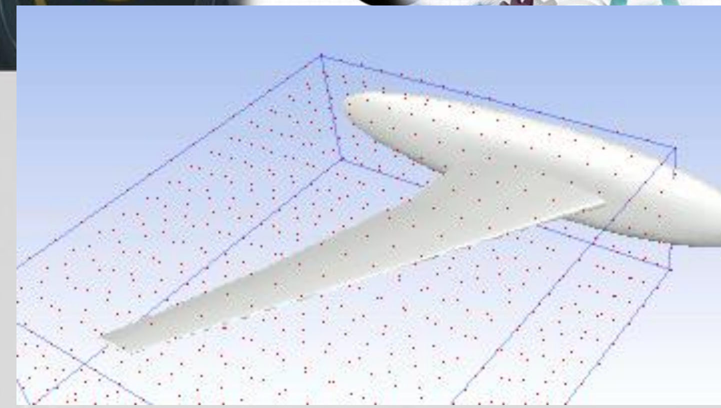
Implementation details for HIRENASD

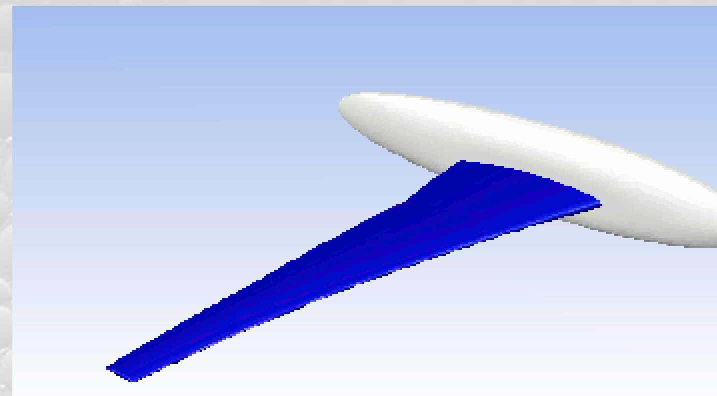
- **Active project with ANSYS Germany & ANSYS Italy focused on HIRENASD case of benchmark of Aeroelastic Prediction Workshop (Thorsten Hansen, Angela Lestari, Benjamin Duda & Domenico Caridi)**
- **HIRENASD challenges: steady case accounting for wing deflection, transient analysis**
- **SOLAR Grids by DLR & NASA available at Workshop site (coarse 1,5 millions)**
- **https://c3.nasa.gov/dashlink/resources/627/**

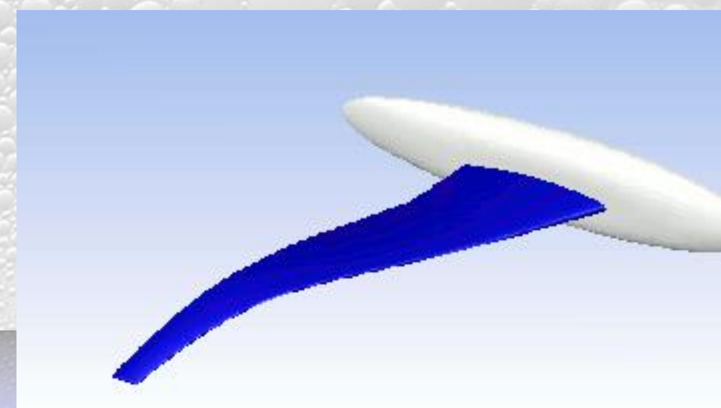


Set-up of FSI run

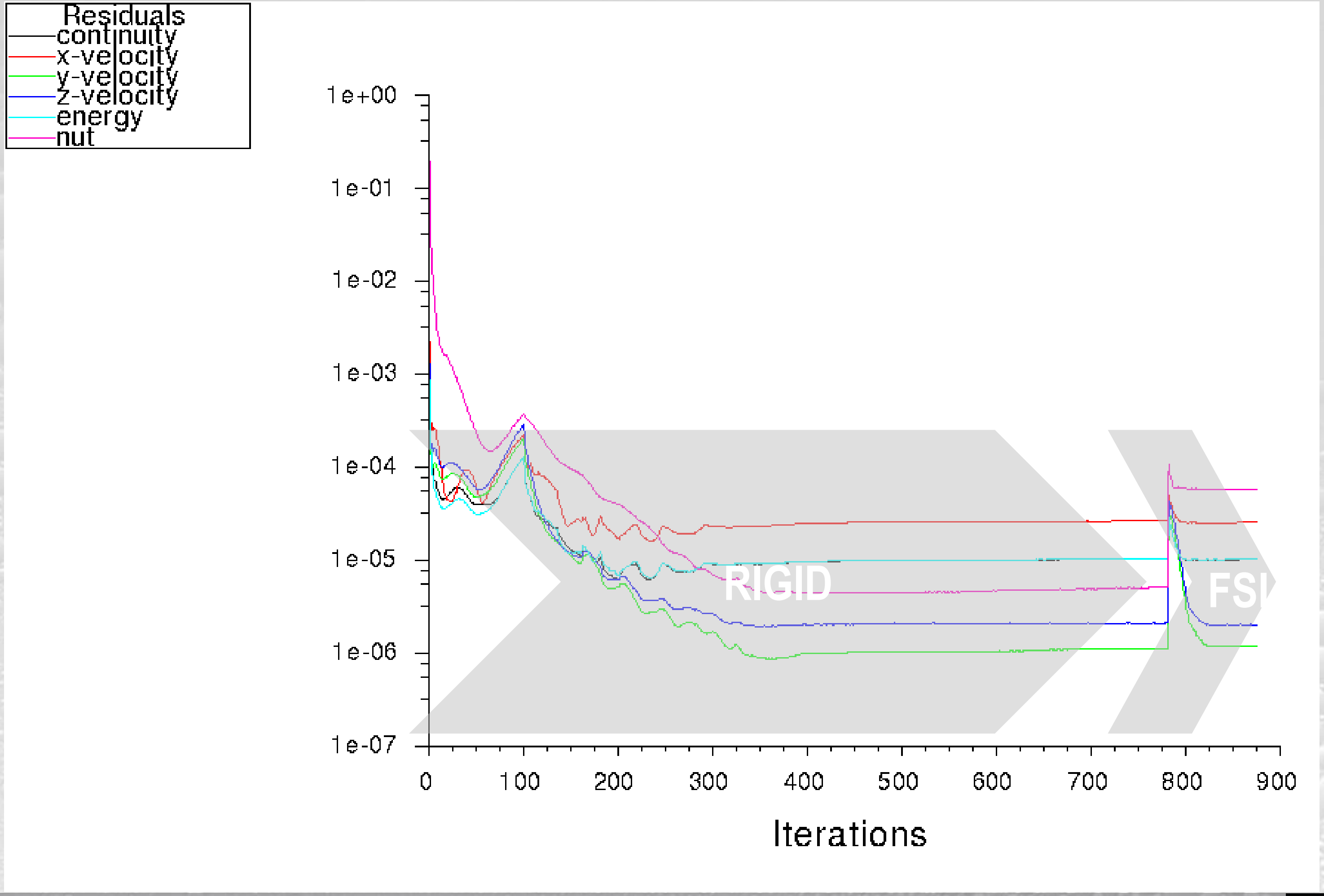
- A specific python command is defined to export FEM solutions from ANSYS Mechanical to RBF Morph
- 6 modes and static analysis results are linked
- RBF Morph set-up
- Modal basis is validated within Fluent thanks to Preview panel
- Update command defined using a scheme function and invoked each 25 iterations as a Fluent calculation activity







Results: convergence history



Results: modal coordinates and forces evolution (updated each 25 its)

```
MODAL STATIC METHOD 6 modes

Modal q = (0.023873514 -0.0014844803 -2.3344388e-05 9.0689438e-05 -6.3392333e-05 2.3980346e-06)
Forces  = (707.5827 -503.60919 -37.307674 163.8091 -201.99422 13.71364)

Modal q = (0.021979975 -0.0014034686 -2.0743131e-05 9.466149e-05 -6.1520127e-05 2.3729543e-06)
Forces  = (651.46045 -476.12601 -33.150494 170.98367 -196.02859 13.570213)

Modal q = (0.022122715 -0.0014103284 -2.0956179e-05 9.4408169e-05 -6.166081e-05 2.3756632e-06)
Forces  = (655.6911 -478.45319 -33.490974 170.52611 -196.47687 13.585705)

Modal q = (0.022112878 -0.0014098863 -2.0941447e-05 9.443238e-05 -6.1651103e-05 2.3755325e-06)
Forces  = (655.39954 -478.30322 -33.46743 170.56984 -196.44594 13.584957)

Modal q = (0.02211373 -0.0014099307 -2.0942344e-05 9.443227e-05 -6.1651912e-05 2.3755556e-06)
Forces  = (655.4248 -478.31827 -33.468864 170.56964 -196.44852 13.58509)
```

Results: rigid vs. flexible

- Trailing edge tip position is monitored at deformed and original position
- Rigid results (@ 780) and flexible results (converged @ 876) demonstrate a strong effect on Cd Cl and Cm
- Comparison with experiments will be completed after the completion of run on fine mesh (ongoing activity)

```
Trailing edge tip deformed

x = 1.0183208
y = 1.2940291
z = 0.0065813386

Trailing edge rigid

x = 1.0181417
y = 1.2938322
z = 0.019315023
```

```
Cl (rigid and deformed)
780      3.57206e-01
876      3.40336e-01

Cd (rigid and deformed)
780      1.66845e-02
876      1.60272e-02

Cm (rigid and deformed)
780      -2.98125e-01
876      -2.81517e-01
```

Conclusions

- FSI modal approach powered by RBF mesh morphing is now an "out of the box" feature of ANSYS Fluent.
- High performances of RBF Morph allows to implement modal FSI with a minimum overhead (process calculation similar to rigid run)
- Overall procedure is reliable and validated with many industrial application (aircraft wings, F1 wings, turbo machine blades, …)
- Several ongoing activities to investigate transient effects (acceleration of 2nd mode HIRENASD, flapping wings, vibration of probes)
- Modes enforcing as a tool for strength analysis (static & transient)

Thank you for your attention!

Dr. Marco Evangelos Biancolini

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YouTube: www.youtube.com/user/RbfMorph