Partnership for Advanced Computing in Europe

RBF Morph: mesh morphing in OpenFoam

Dr. Marco Evangelos Biancolini
University of Rome "Tor Vergata"

Tor Vergata

HPC enabling of OpenFOAM for CFD applications @ CINECA, 26-28 March 2014
Cineca - BOLOGNA

RBF Morph Training – PRACE School 2013

Session #1

General Introduction of RBF Morph, Features with examples
http://videolectures.net/prace2013_biancolini_rbf_morph/

Session #2

Basic Usage of RBF Morph, Examples and Live demonstration
http://videolectures.net/prace2013_biancolini_rbf_morph_hands_on/

Session #3

Advanced Usage of RBF Morph, Multi-solve, Free surface Deformation, STL target, Back to CAD, WB coupling

RBF Morph Training Material

Web Portal: www.rbf-morph.com frequently updated with News

Download Area: http://rbf-morph.com/index.php/download

- *animations, technical papers, conference presentations*
- *for registered users (usr:ANSYS_COM, pwd:ANSYS_COM)*

YouTube: www.youtube.com/user/RbfMorph video tutorials

Documentation Package (on box.com reserved area):

- *User Guide / Installation Notes*
- *Tutorials (complete of support files folders)*

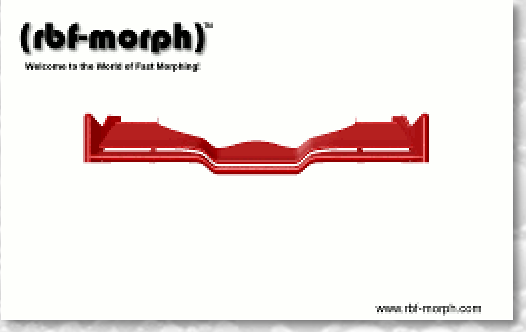
Linkedin: https://www.linkedin.com/company/rbf-morph/

E-mail support: info@rbf-morph.com

RBF Morph Training

General Introduction of RBF Morph, Features with examples

Dr. Marco Evangelos Biancolini



Outline

- RBF Morph tool presentation
- Ongoing Researches
- Industrial Applications
- Hands On

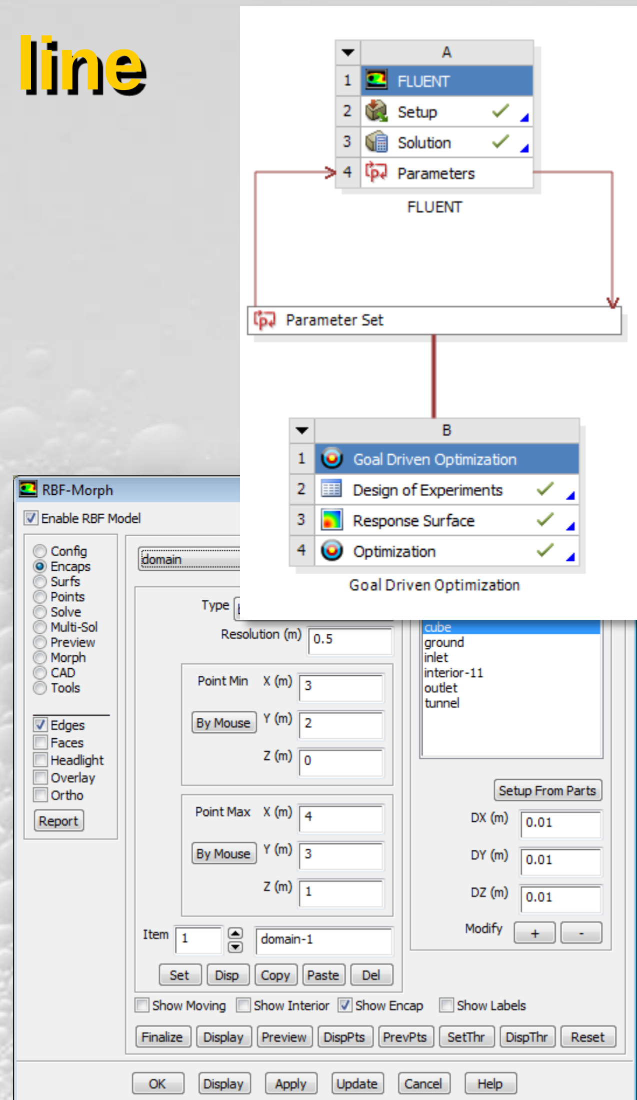
RBF Morph tool presentation

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**!).

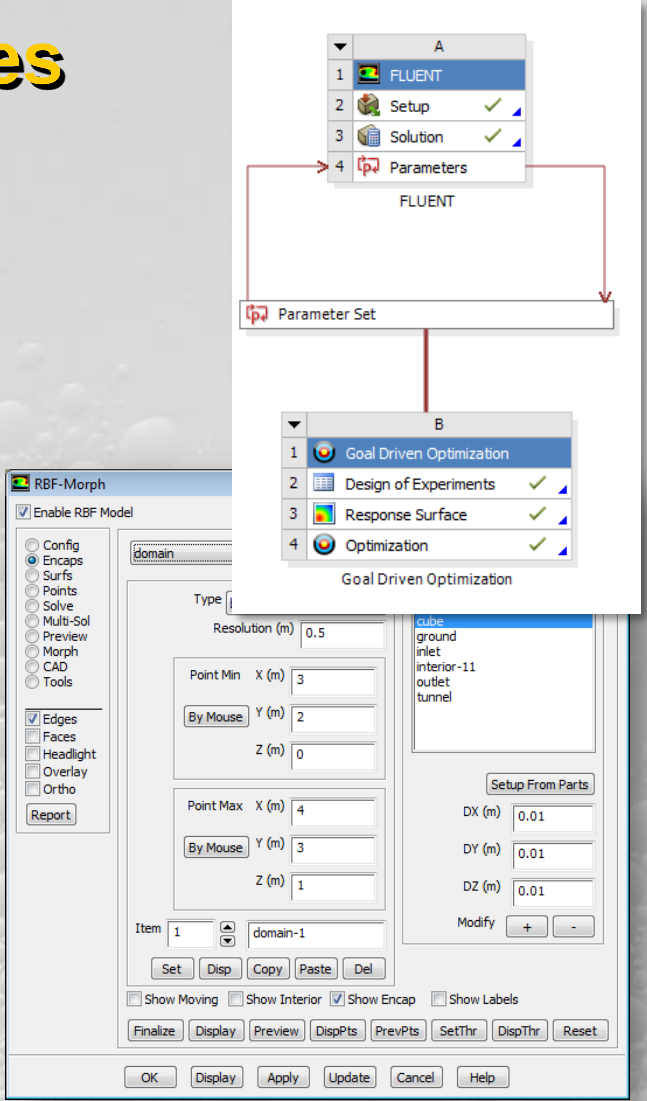
RBF Morph software line

- Awarded mesh morphing software available as an add-on for **ANSYS Fluent** CFD solver
- HPC RBF general purposes library (state of the art algorithms, parallel, GPU).
- Stand alone morphing software + smoothing commands (OpenFoam, Nastran, Step, STL, Elsa, CFD++)
- ANSYS Mechanical **ACT module** (first release planned in June 2014)



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**).



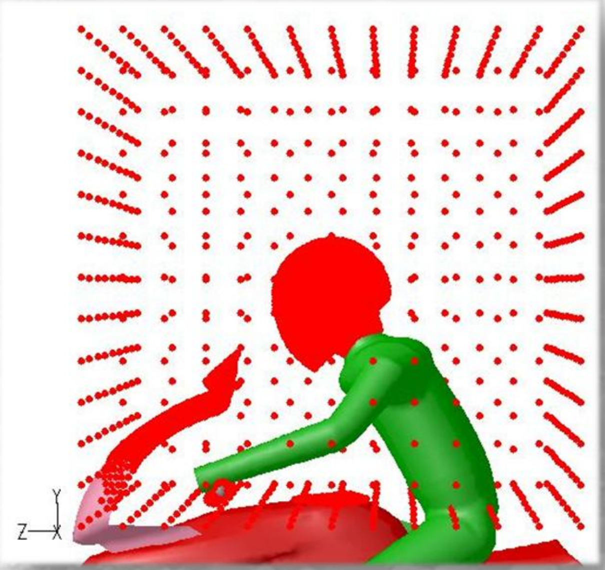
Mesh Morphing with Radial Basis Functions

- 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**.

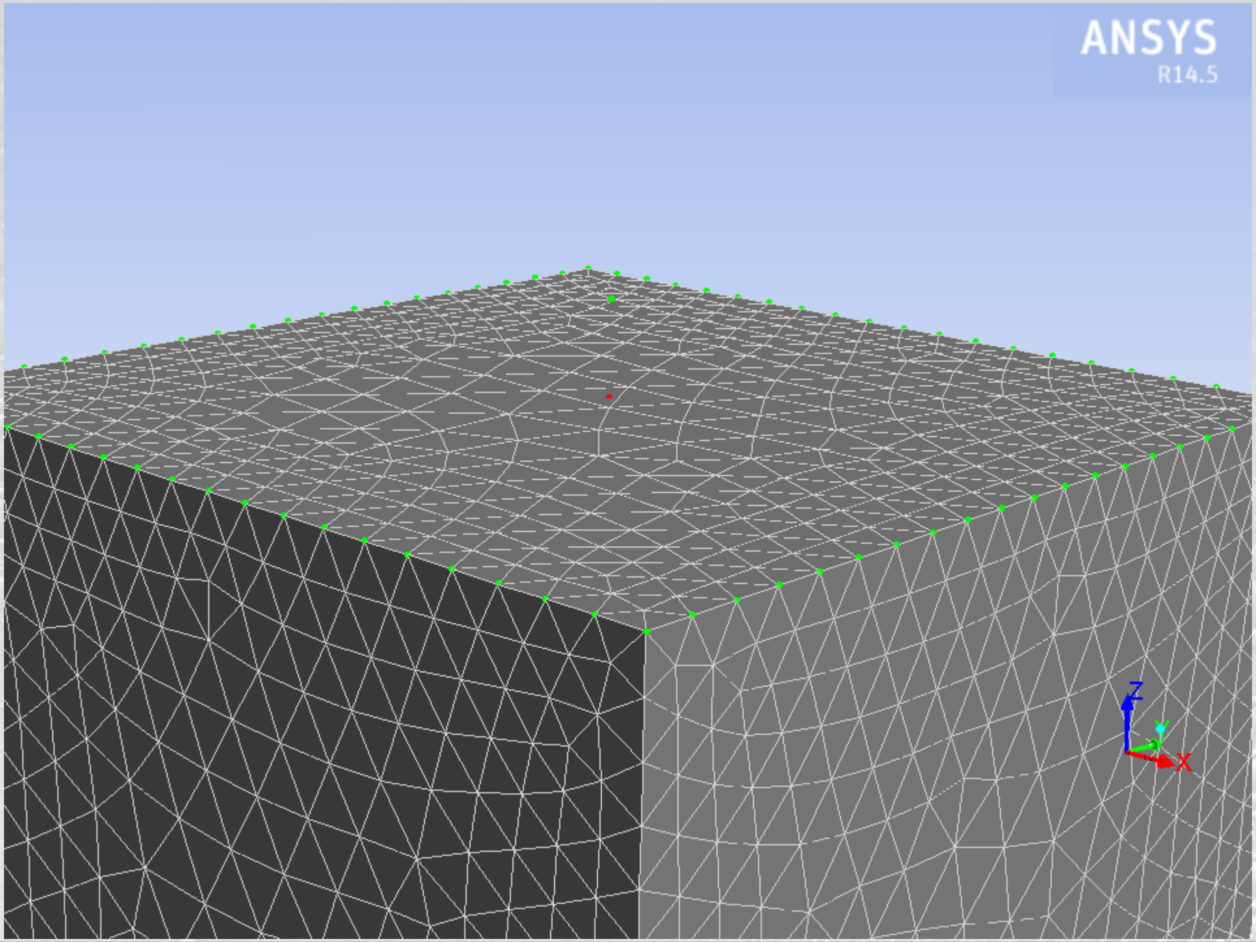
- The RBF problem definition does not depend on the mesh

- Radial Basis Function interpolation is used to derive the displacement in **any location** in the space, each component of the displacement is interpolated:

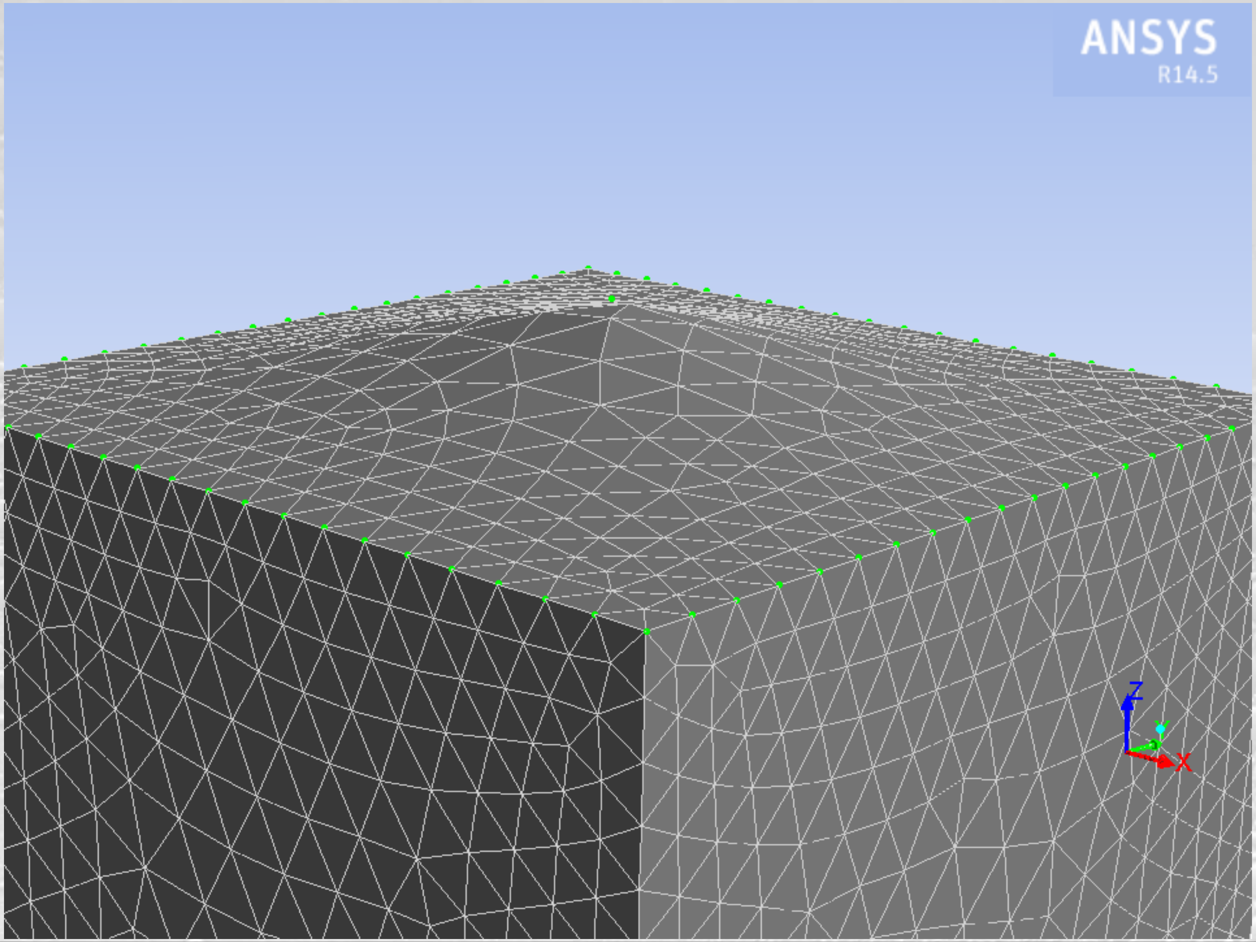
$$
\begin{cases}
v_x = s_x(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^x \phi\left(\left\|\mathbf{x} - \mathbf{x}_{k_i}\right\|\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\
v_y = s_y(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^y \phi\left(\left\|\mathbf{x} - \mathbf{x}_{k_i}\right\|\right) + \beta_1^y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



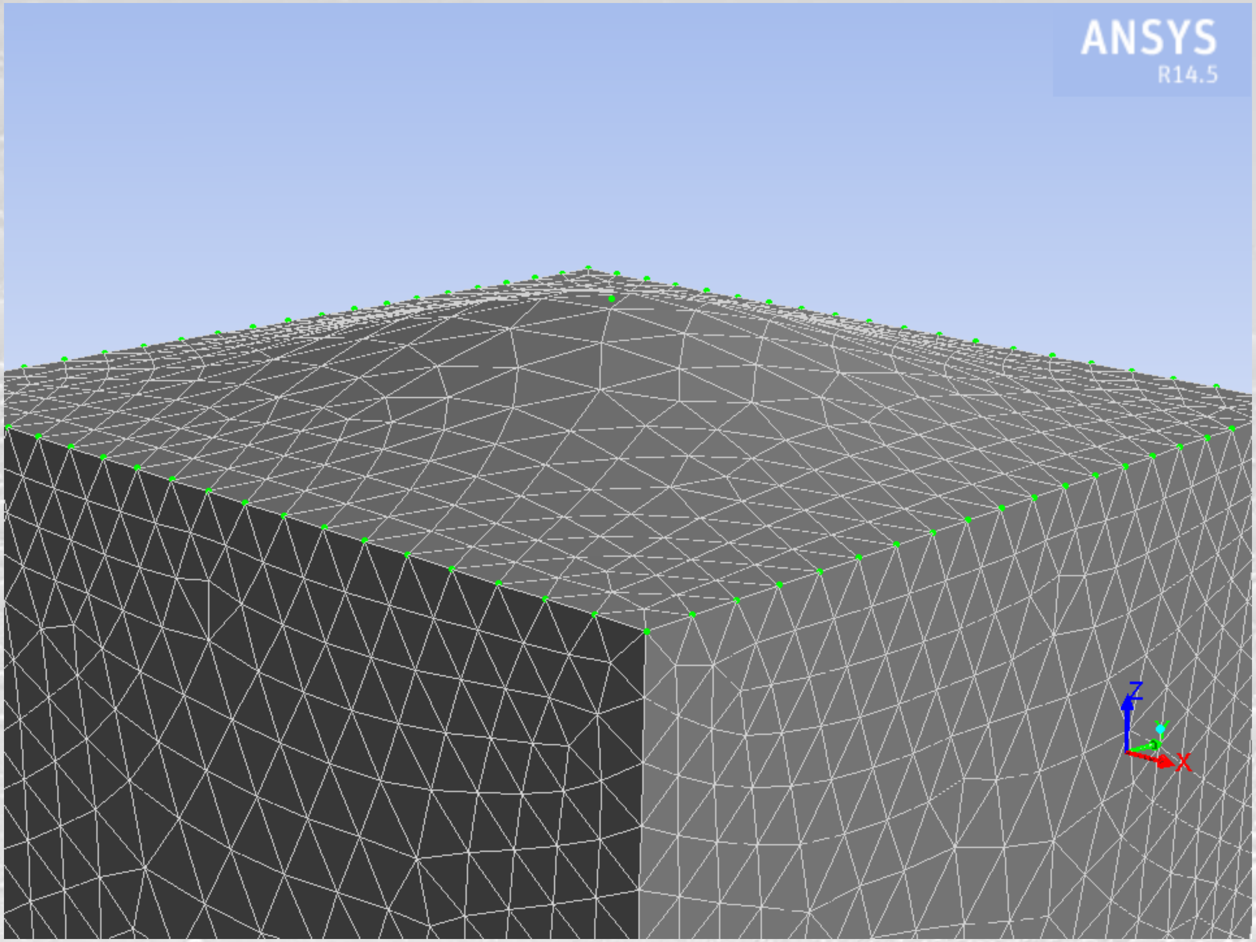
One pt at center 80 pts at border



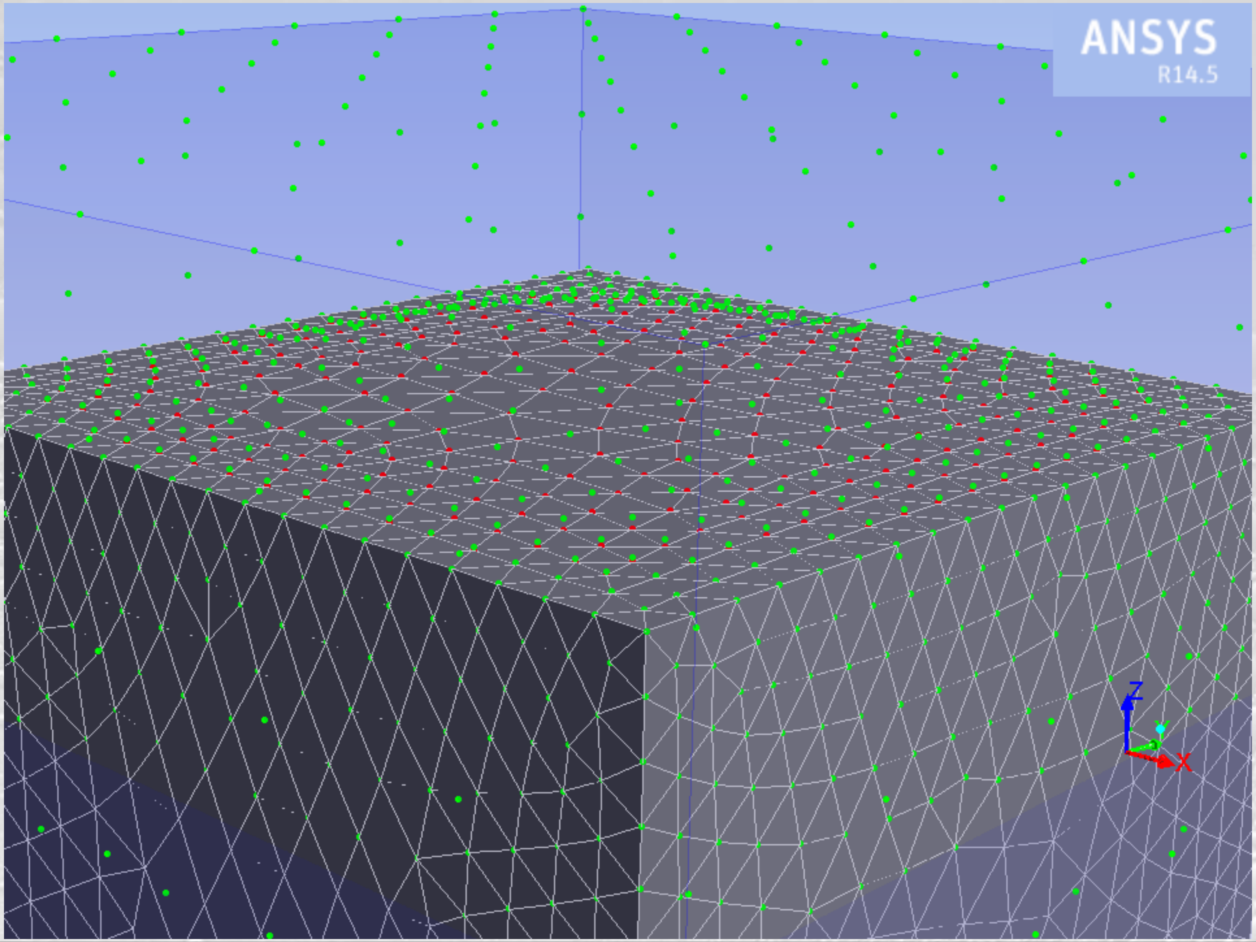
Effect on surface (gs-r)



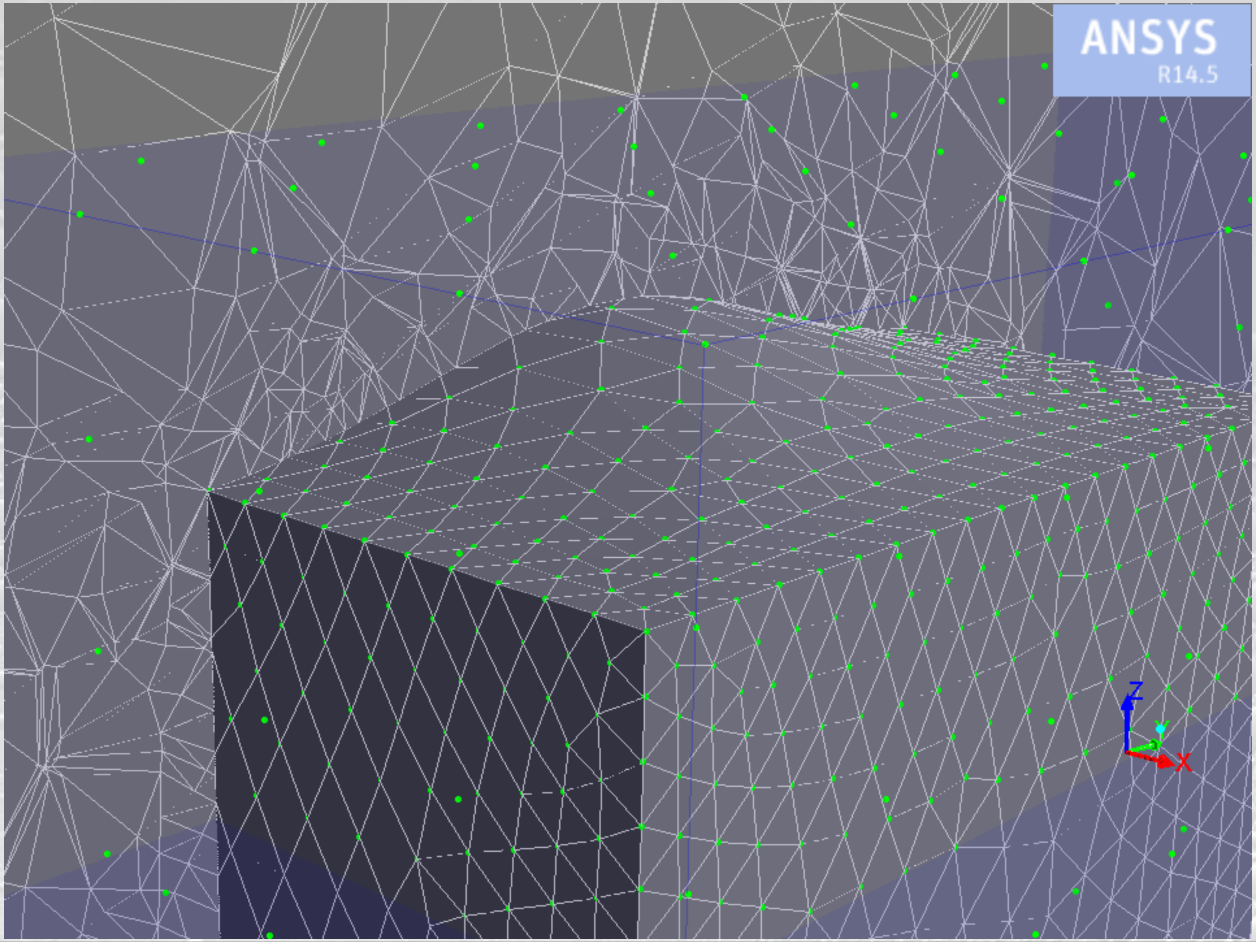
Effect on surface (cp-c4)



Control of volume mesh (1166 pts)

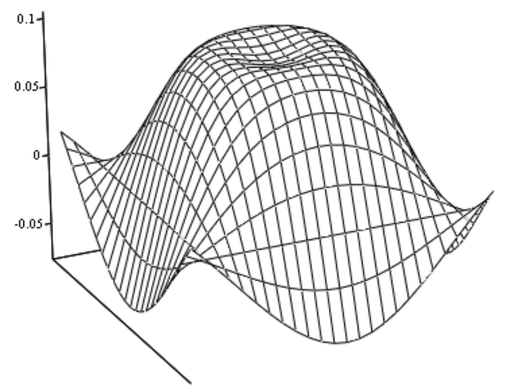


Morphing the volume mesh



Background: RBF Theory

- 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**. This approach is valid for both surface shape changes and volume mesh smoothing.
- 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, so it is also available in every grid node.
- An interpolation function composed by a radial basis and a polynomial is defined.



$$s(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i \phi(\|\mathbf{x} - \mathbf{x}_i\|) + h(\mathbf{x})$$

$$h(\mathbf{x}) = \beta + \beta_1 x + \beta_3 y + \beta_4 z$$

Background: RBF Theory

- A radial basis fit exists if desired values are matched at source points with a null poly contribution
- The fit problem is associated with the solution of a linear system
- **M** is the interpolation matrix
- **P** is the constraint matrix
- **g** are the scalar values prescribed at source points
- γ and **β** are the fitting coefficients

$$s(\mathbf{x}_{k_i}) = g(\mathbf{x}_{k_i}) \quad 1 \le i \le N$$

$$0 = \sum_{i=1}^{N} \gamma_i q(\mathbf{x}_{k_i})$$

$$\begin{pmatrix} \mathbf{M} & \mathbf{P} \\ \mathbf{P}^{\mathrm{T}} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \boldsymbol{\gamma} \\ \boldsymbol{\beta} \end{pmatrix} = \begin{pmatrix} \mathbf{g} \\ \mathbf{0} \end{pmatrix}$$

$$M_{ij} = \phi\left(\left\|\mathbf{x}_{k_i} - \mathbf{x}_{k_j}\right\|\right) \quad 1 \le i \quad j \le N$$

$$\mathbf{P} = \begin{pmatrix} 1 & x_{k_1}^0 & y_{k_1}^0 & z_{k_1}^0 \\ 1 & x_{k_2}^0 & y_{k_2}^0 & z_{k_2}^0 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{k_N}^0 & y_{k_N}^0 & z_{k_N}^0 \end{pmatrix}$$

Background: RBF Theory

- The radial function can be fully or compactly supported. The bi-harmonic kernel fully supported gives the best results for smoothing.
- For the smoothing problem each component of the displacement prescribed at the source points is interpolated as a single scalar field.

Radial Basis Function	$\phi(r)$
Spline type (R_n)	$\lvert r\rvert^n$, n odd
Thin plate spline (TPS_n)	$\lvert r\rvert^n \log\lvert r\rvert$, n even
Multiquadric(MQ)	$\sqrt{1+r^2}$
Inverse multiquadric (IMQ)	$\frac{1}{\sqrt{1+r^2}}$
Inverse quadratic (IQ)	$\frac{1}{1+r^2}$
Gaussian (GS)	e^{-r^2}

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

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

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

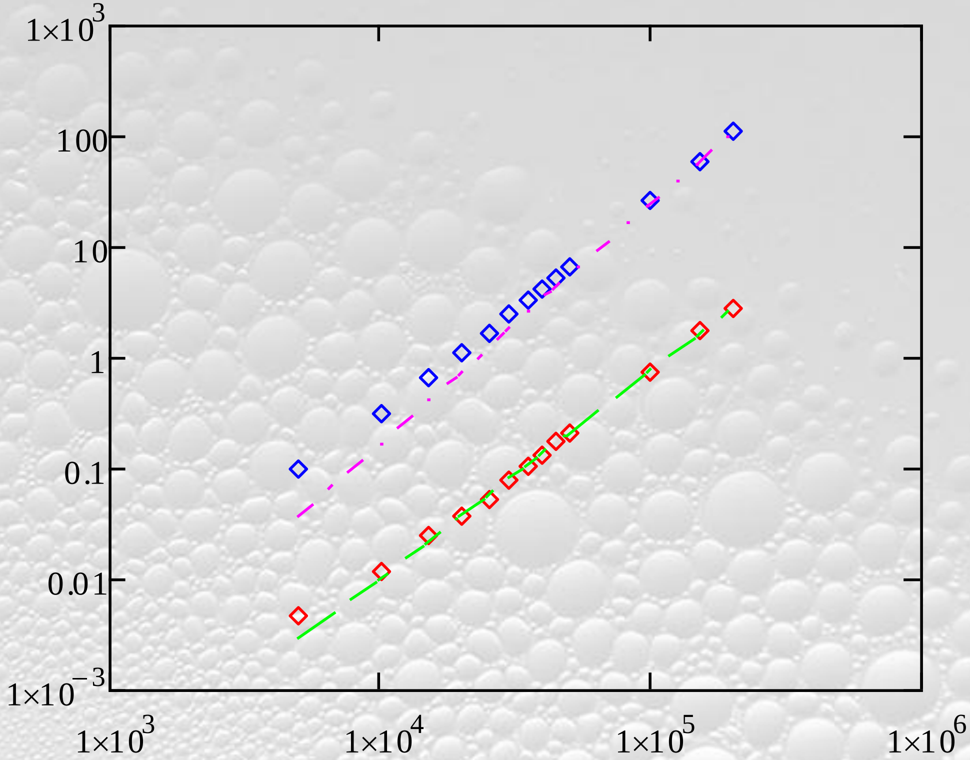
#points	CPU	GPU	speed up
5000	0,098402	0,004637	21,2
10000	0,319329	0,011746	27,2
15000	0,667639	0,024982	26,7
20000	1,135127	0,038352	29,6
25000	1,721781	0,054019	31,9
30000	2,451661	0,079459	30,9
35000	3,306897	0,108568	30,5
40000	4,286706	0,134978	31,8
45000	5,390029	0,181181	29,7
50000	6,707721	0,2135	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:

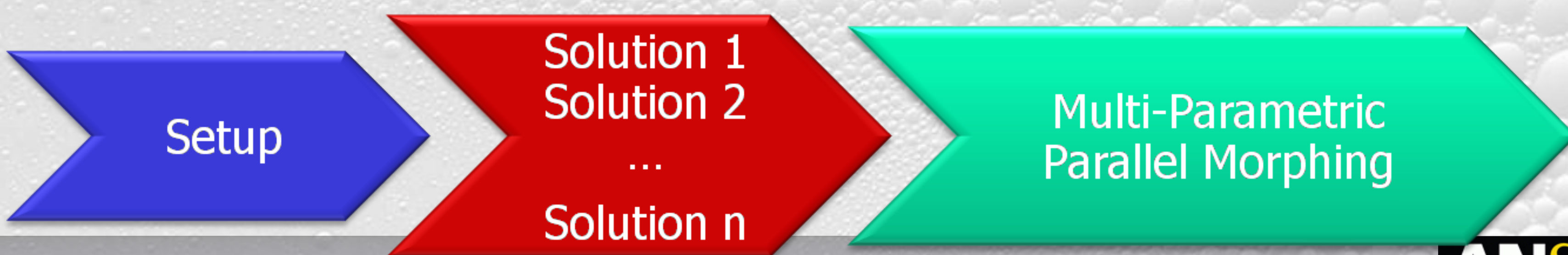
  GPU: 59 s

  CPU: 2783 s



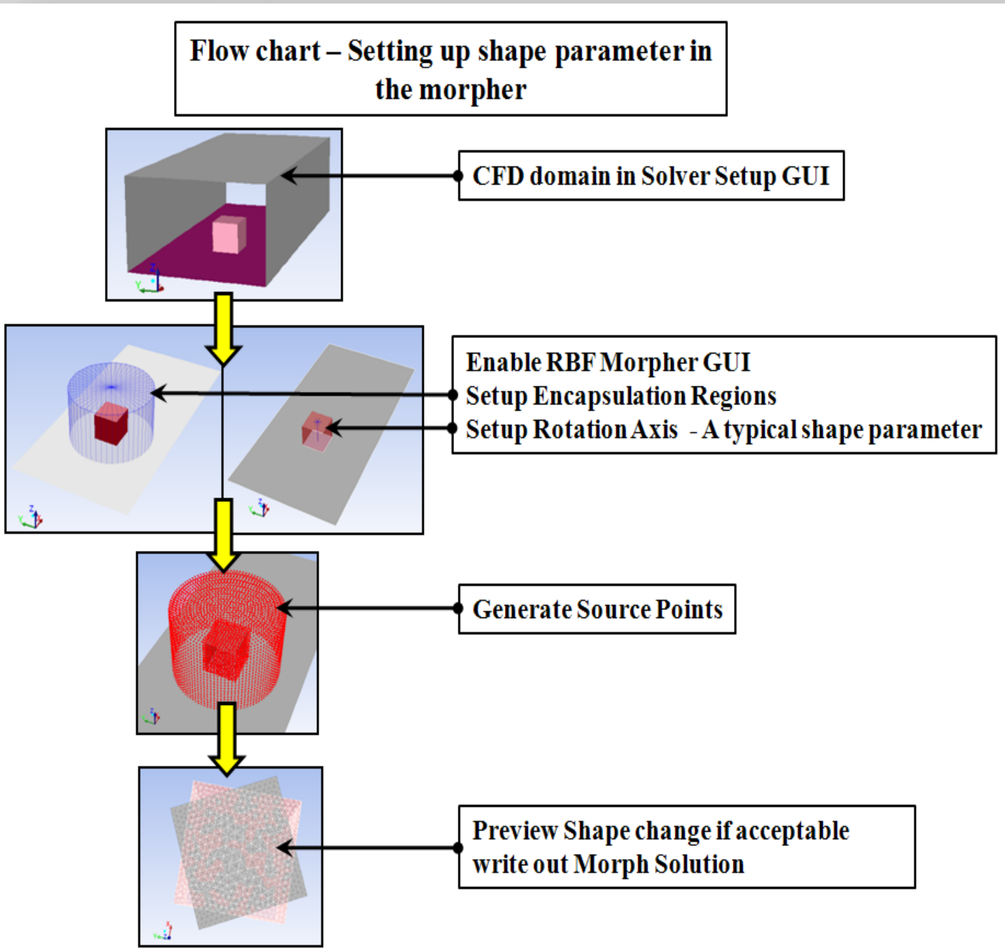
How it Works: the work-flow

- *RBF Morph* basically requires three different steps:
- **Step 1 setup** and definition of the problem (source points and displacements).
- **Step 2 fitting** of the RBF system (write out .rbf + .sol).
- **Step 3 [SERIAL or PARALLEL] morphing** of the surface and volume mesh (available also in the **CFD solution stage** it requires only baseline mesh and .rbf + .sol files).



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**.



How it Works: Fluent parallel morphing

- **Interactive** update using the GUI **Multi-Sol** panel and the Morph/Undo commands.
- **Interactive** update using **sequential morphing** by the TUI command `(rbf-smorph)`.
- **Batch** update using the **single morphing** command `(rbf-morph)` in a journal file (the RBF Morph DOE tool allows to easily set-up a run).
- **Batch** update using several **sequential morphing** commands in a journal file.
- Link shape amplifications to **Fluent custom parameters** driven by **Workbench** (better if using **DesignXplorer**).
- More options (transient, FSI, modeFRONTIER, batch RBF fit …)

How it Works: stand alone version

- Shape modifications can be defined using the **stand alone** RBF Morph GUI (CGNS plot based, accepts CGNS and stl) and/or **Fluent Add On** for each shape modifications 2 files are stored (.rbf .sol).
- Volume morphing can be executed using specific **morphing commands** (input: original mesh, shape modifications, shape amplifications) or directly **embedding** the smoothing library
- Notice that even in the case of **huge meshes** just the shape modifications files are required; with a very **small demand of storage** because just the points and the coefficients of the RBF are stored.
- A shape **parametric** calculation grid is obtained

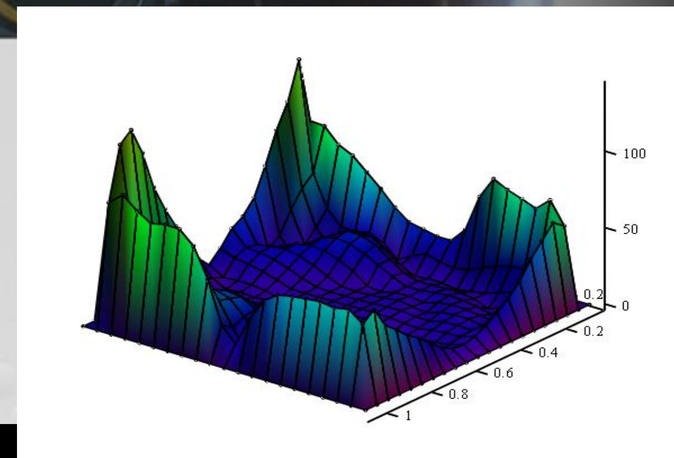
Ongoing Researches about RBF

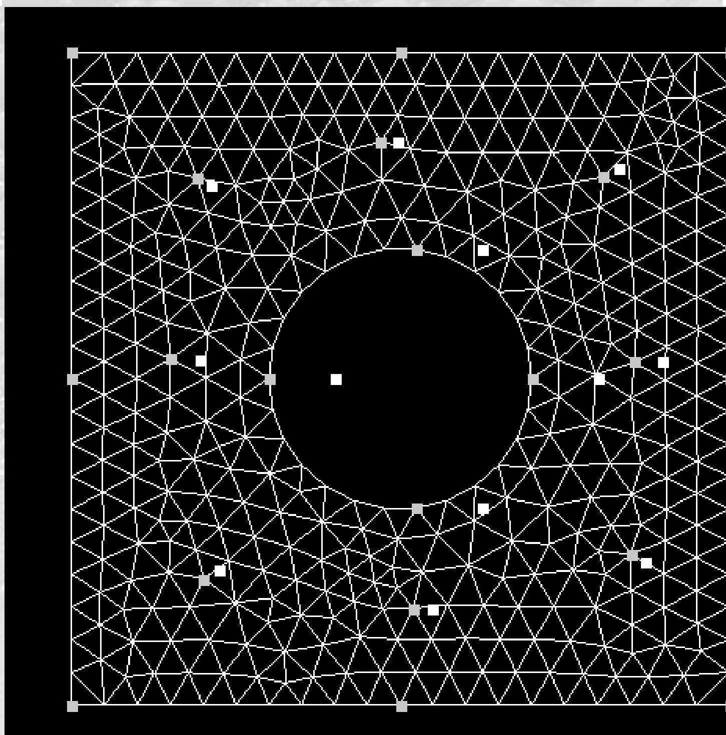
Ongoing RBF researches

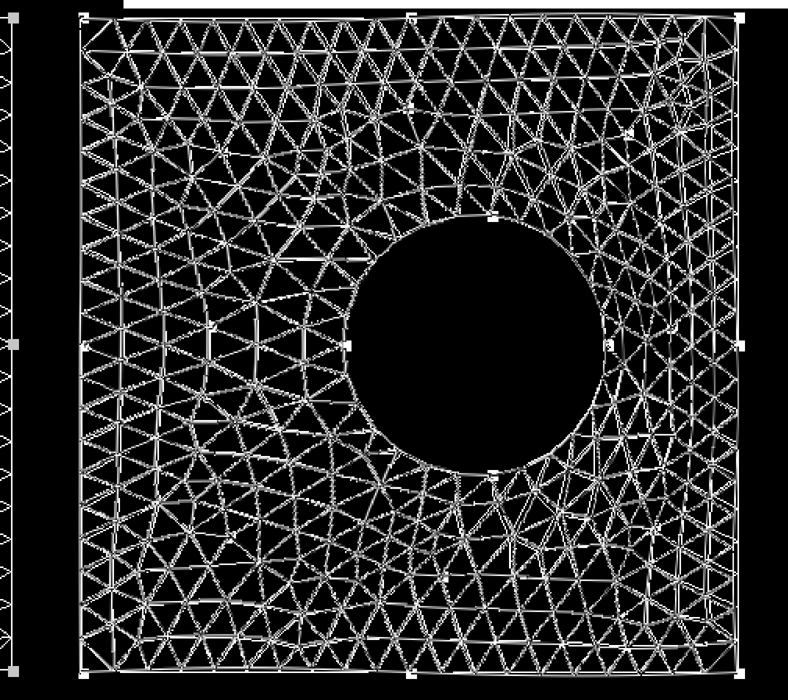
- RBF for **meta modeling** (DOE optimisation) including sensitivity data (adjoint solver)
- Mapping of **magnetic** loads
- Interpolation of **hemodynamic** flow fields acquired in vivo
- Strain and **stress calculation** (experimental data, coarse FEM, isostatic lines)
- **Implicit surface** modeling (used for STL targets)
- FSI **pressure** mapping

RBF for the image analysis of deformations

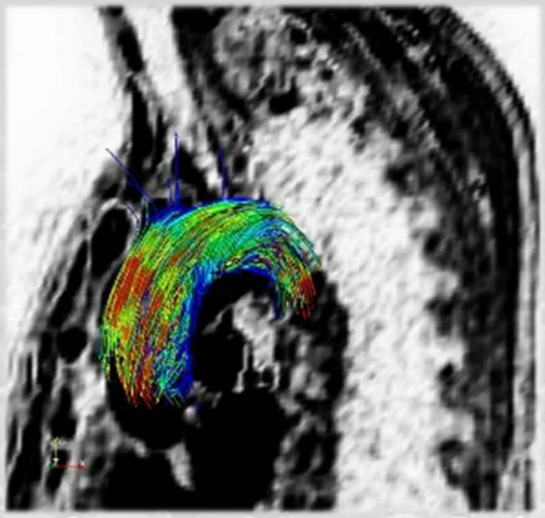
42.8% below 5%
17.4% in the range 5%-10%
14.9% in the range 10%-20%
13.9% in the range 20%-50%
11.0% over 50%

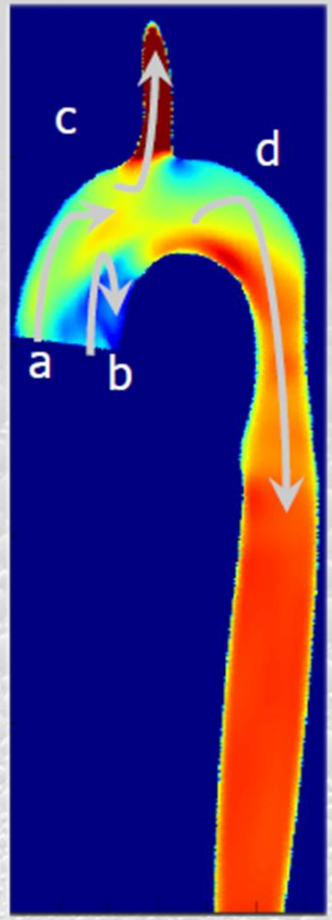


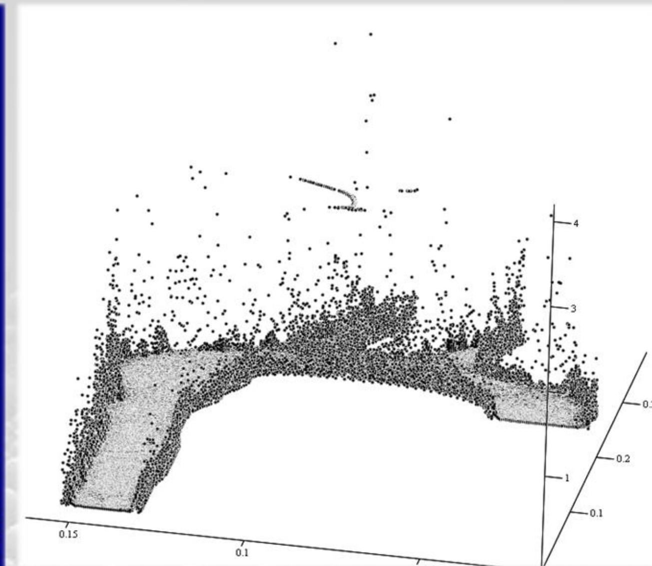




RBF for the interpolation of hemodynamics flow pattern







CINECA SCAI
SuperComputing Applications and Innovation

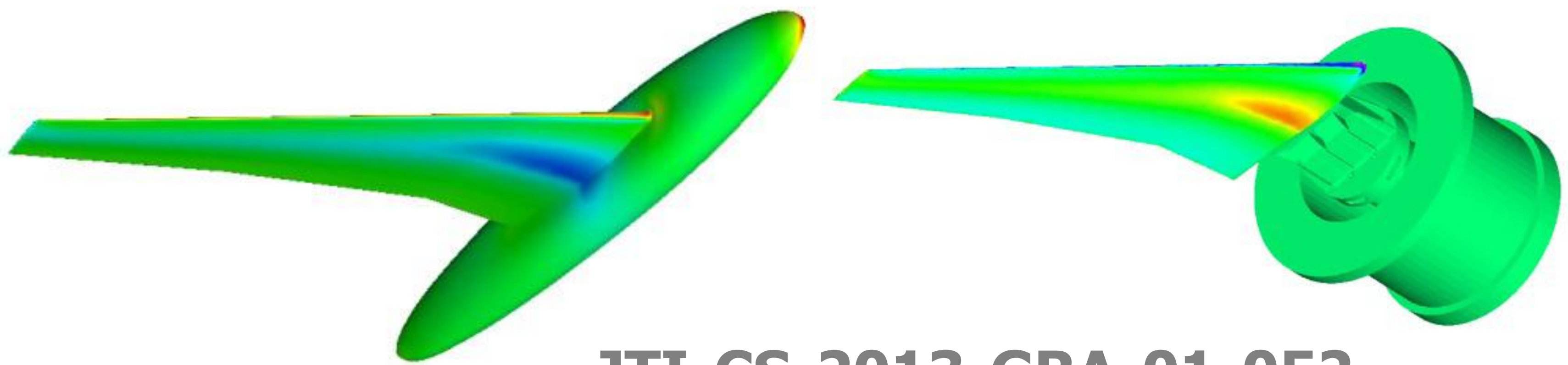
82% below 5%
5% in the range 5%-10%
8% in the range 10%-20%
4% in the range 20%-50%
1% over 50%

HIRENASD & RIBES

CLEANSKY

R.I.B.E.S.

Radial basis functions at fluid **I**nterface **B**oundaries to **E**nvelope flow results for advanced **S**tructural analysis

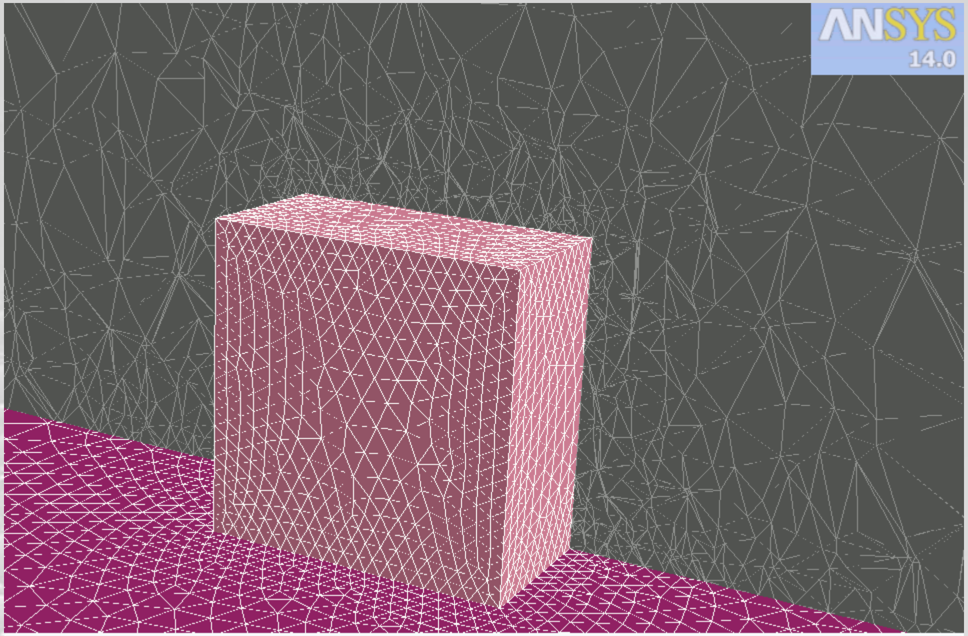


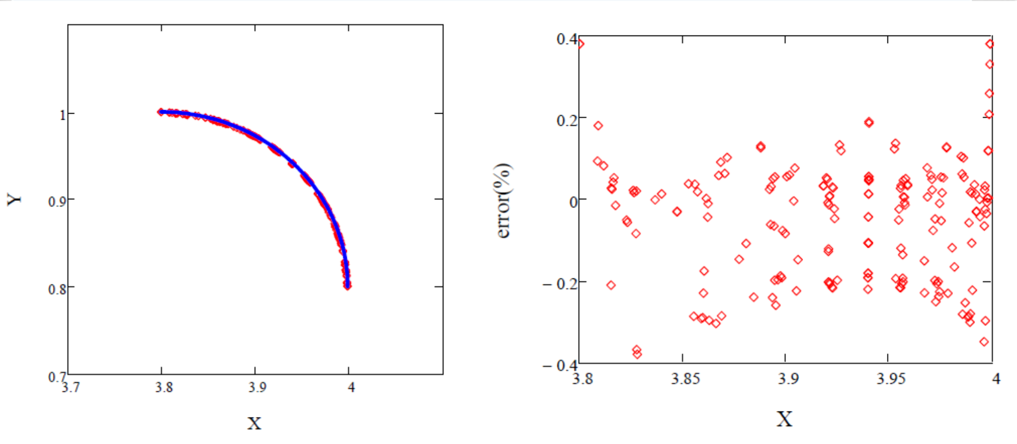
JTI-CS-2013-GRA-01-052

	X direction	Y direction	Z direction
CFD model (N)	2.6000204E+01	3.0621133E+02	5.7518198E+03
FEM model (N)	2.94580E+01	3.163942E+02	5.809278E+03
ERROR (%)	11.7	3.2	1.0

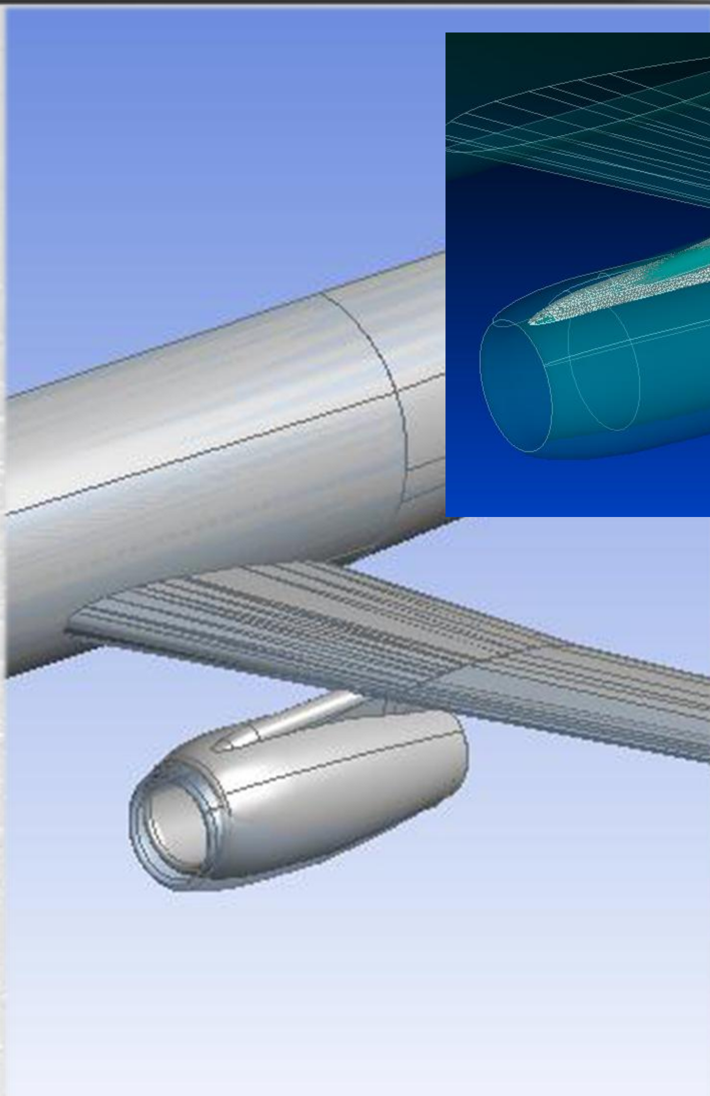
CAD controlled surfaces

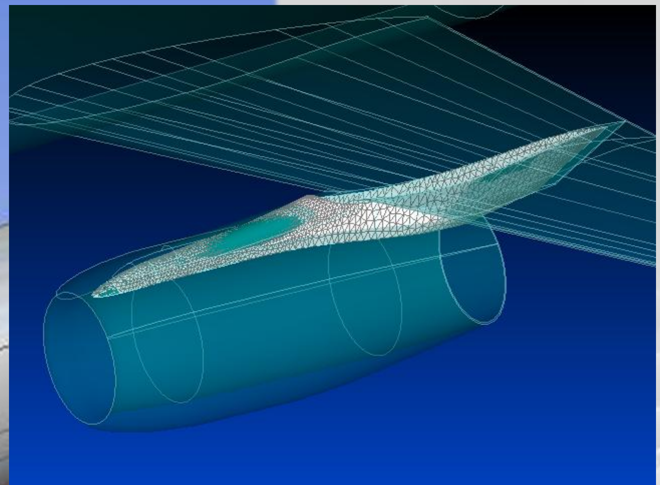
- A new shape known in advance can be inserted using an **STL target**
- In the example a **fillet** with radius in the range 20-30 mm is applied to one edge of the 1000 mm side cube
- Shape **blending** allows a continuous variation
- Accuracy of implicit surface is validated against reference analytic geometry

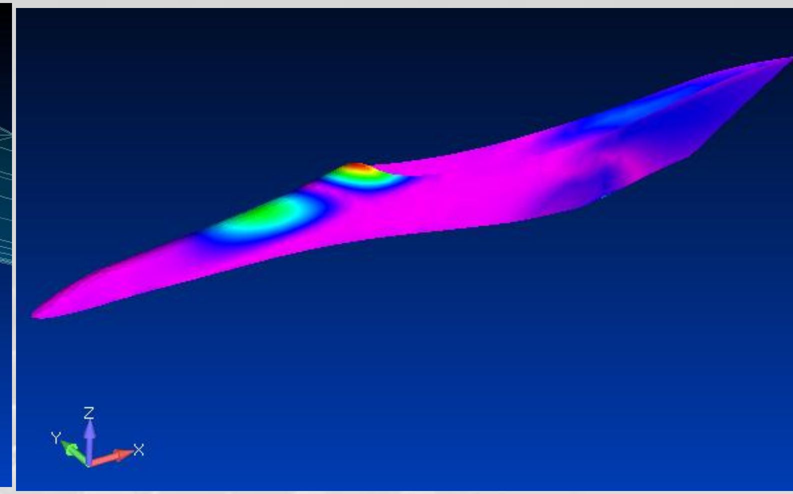


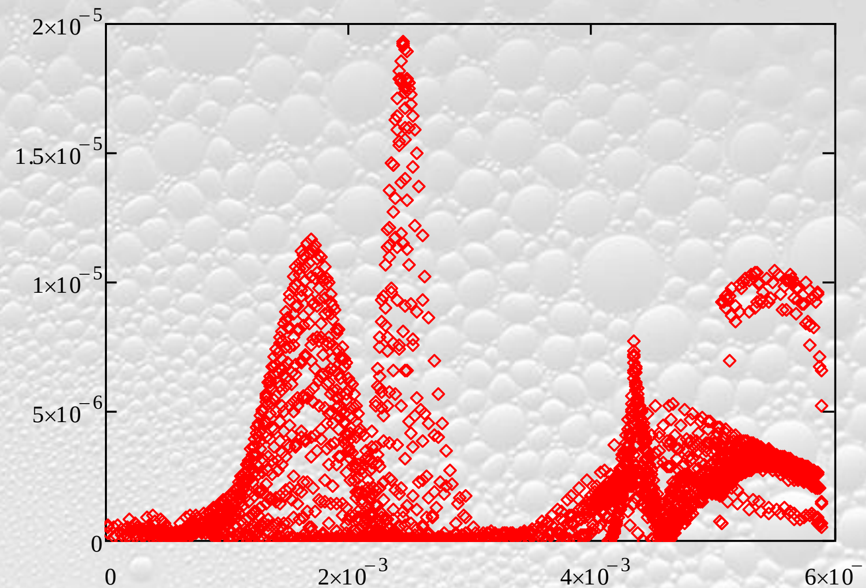


MESH2CAD - NURBS

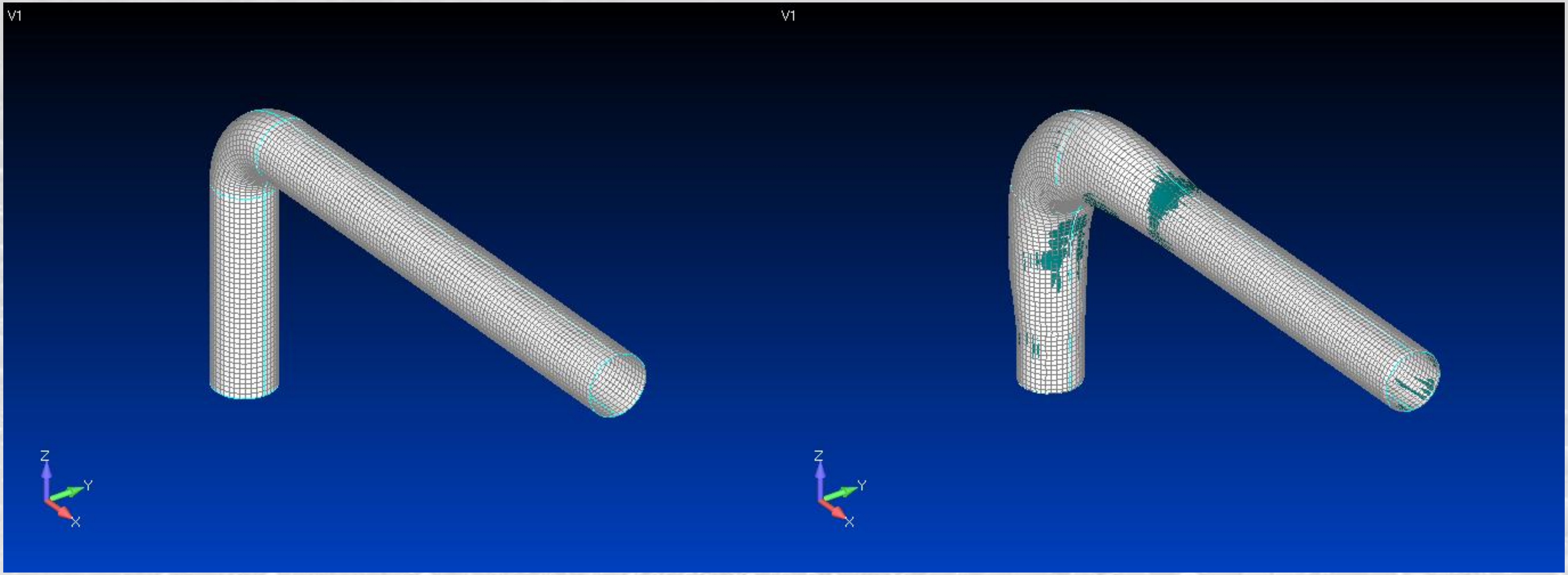








Adjoint Sculpting

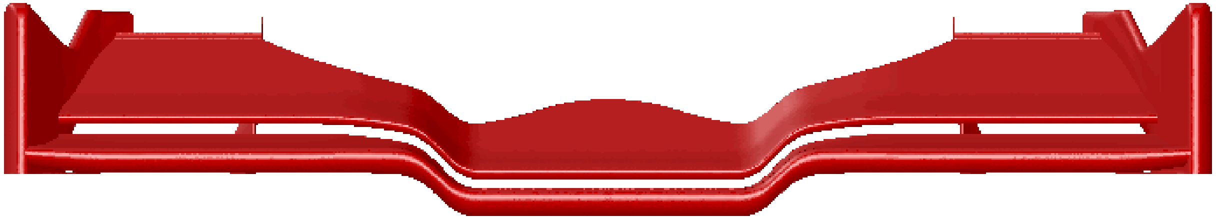


Industrial Applications

Formula 1 Front Wing

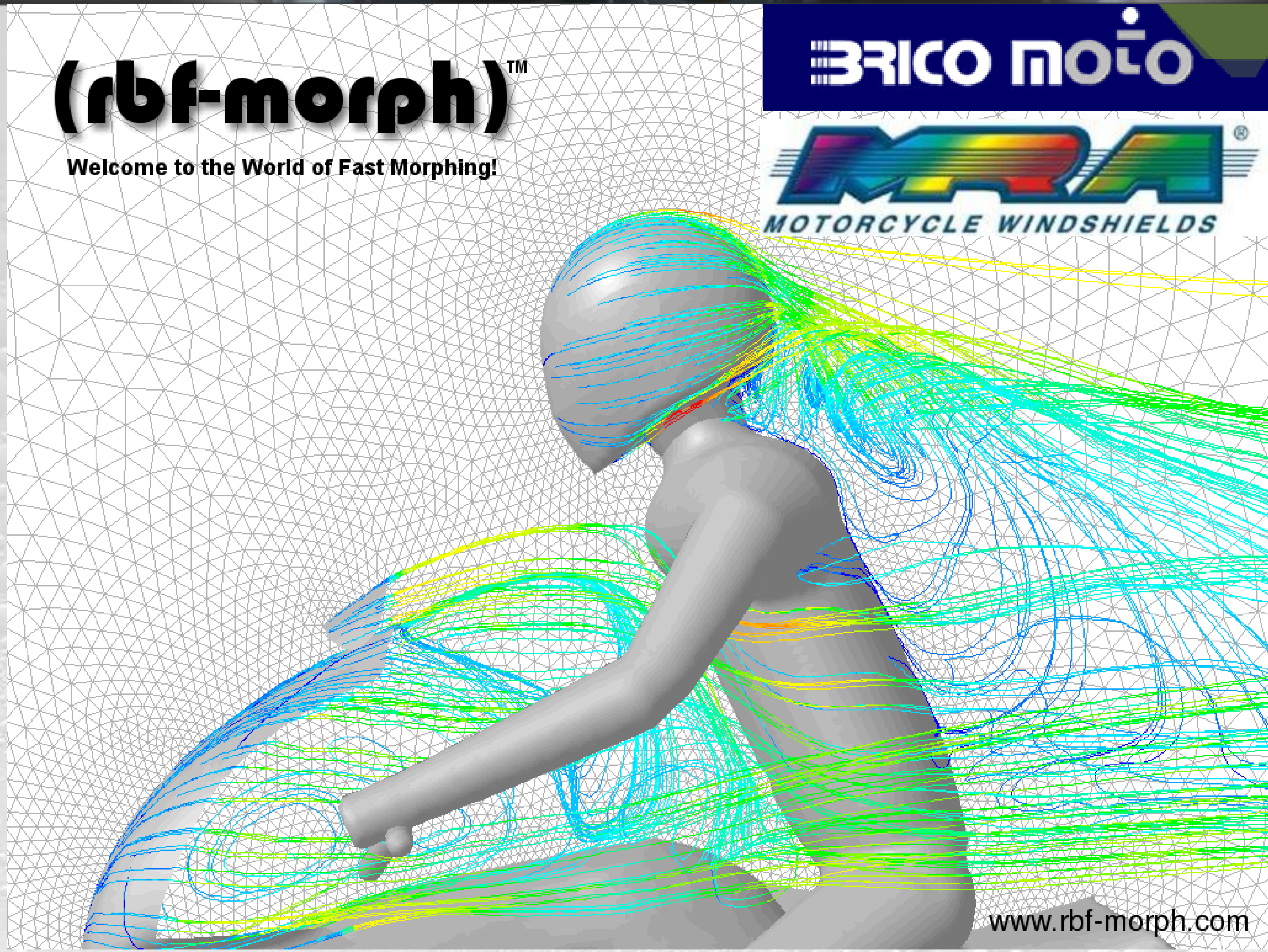
(rbf-morph)™

Welcome to the World of Fast Morphing!

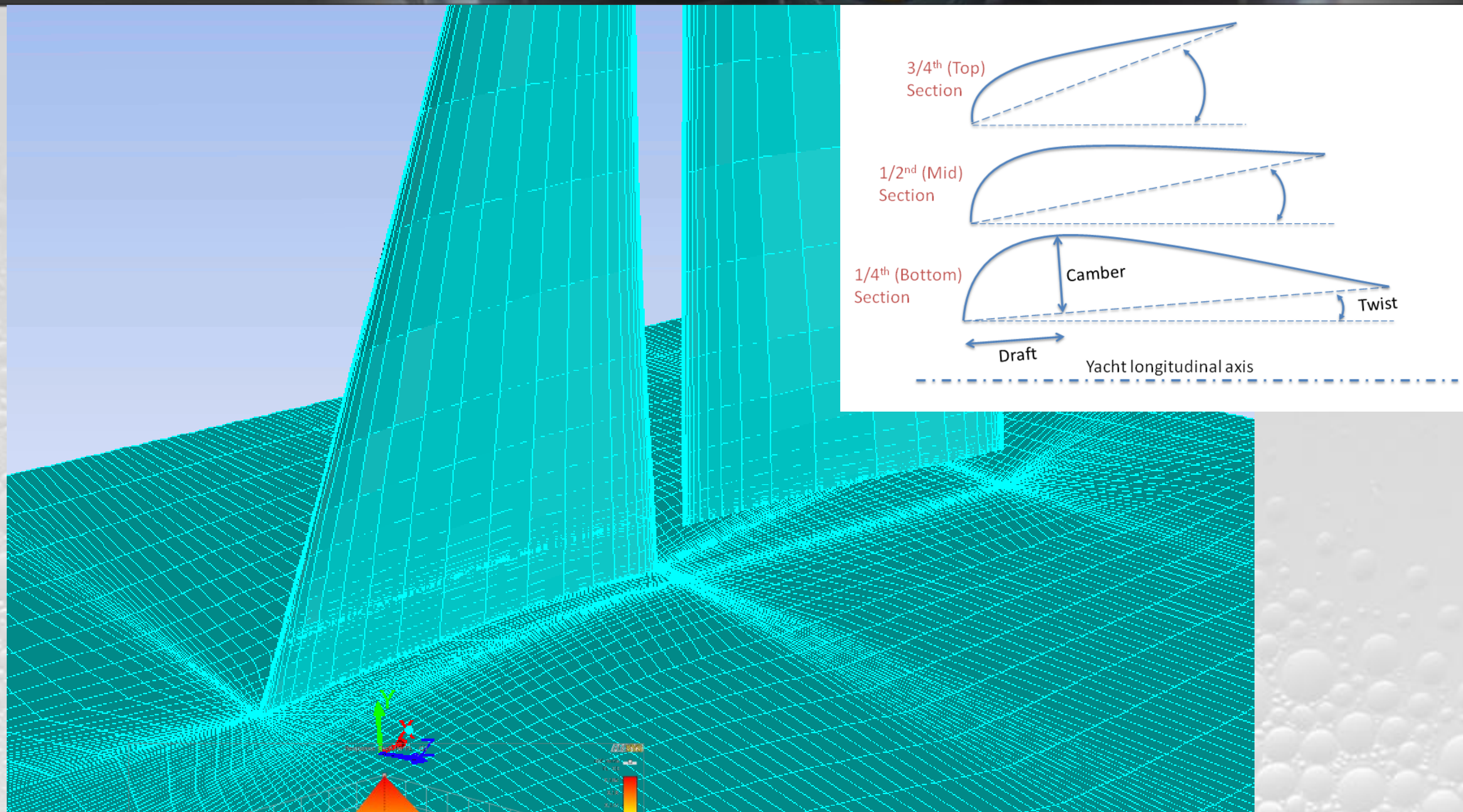


www.rbf-morph.com

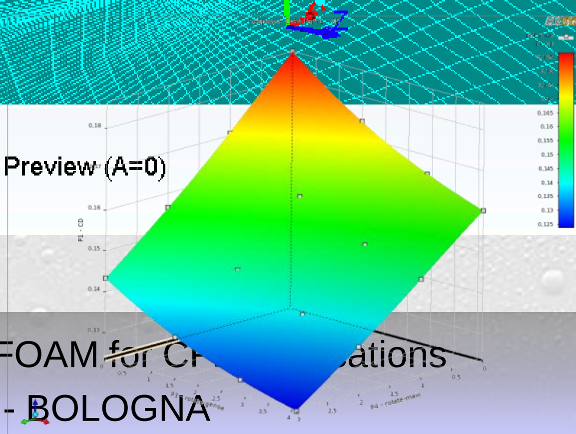
Motorbike Windshield (Bricomoto, MRA)



Sails Trim (Ignazio Maria Viola, University of Newcastle)



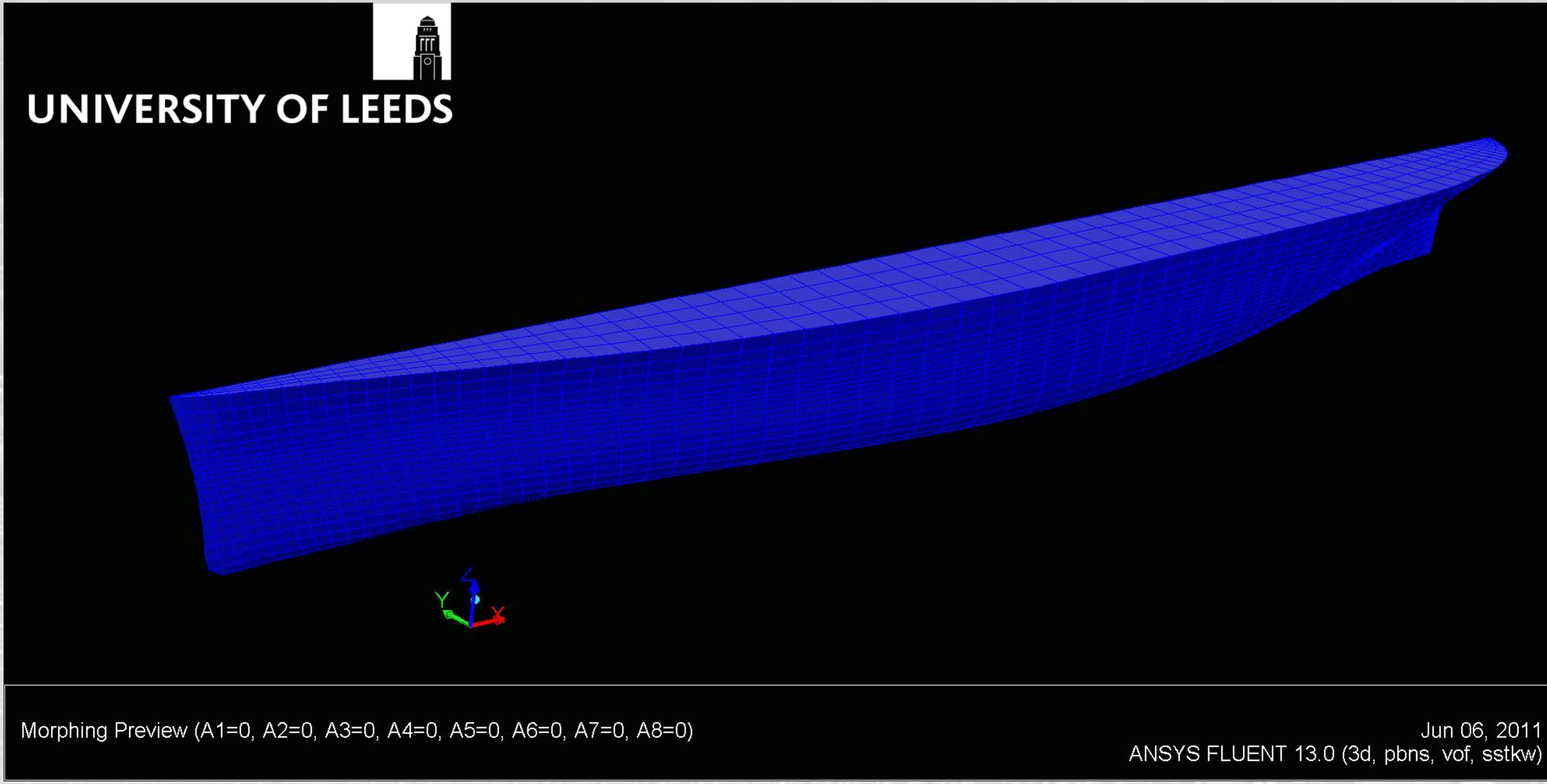
Morphing Preview (A=0)



Newcastle University
Yacht and superyacht consultancy and research
school of marine science and technology

ignazio.viola@ncl.ac.uk

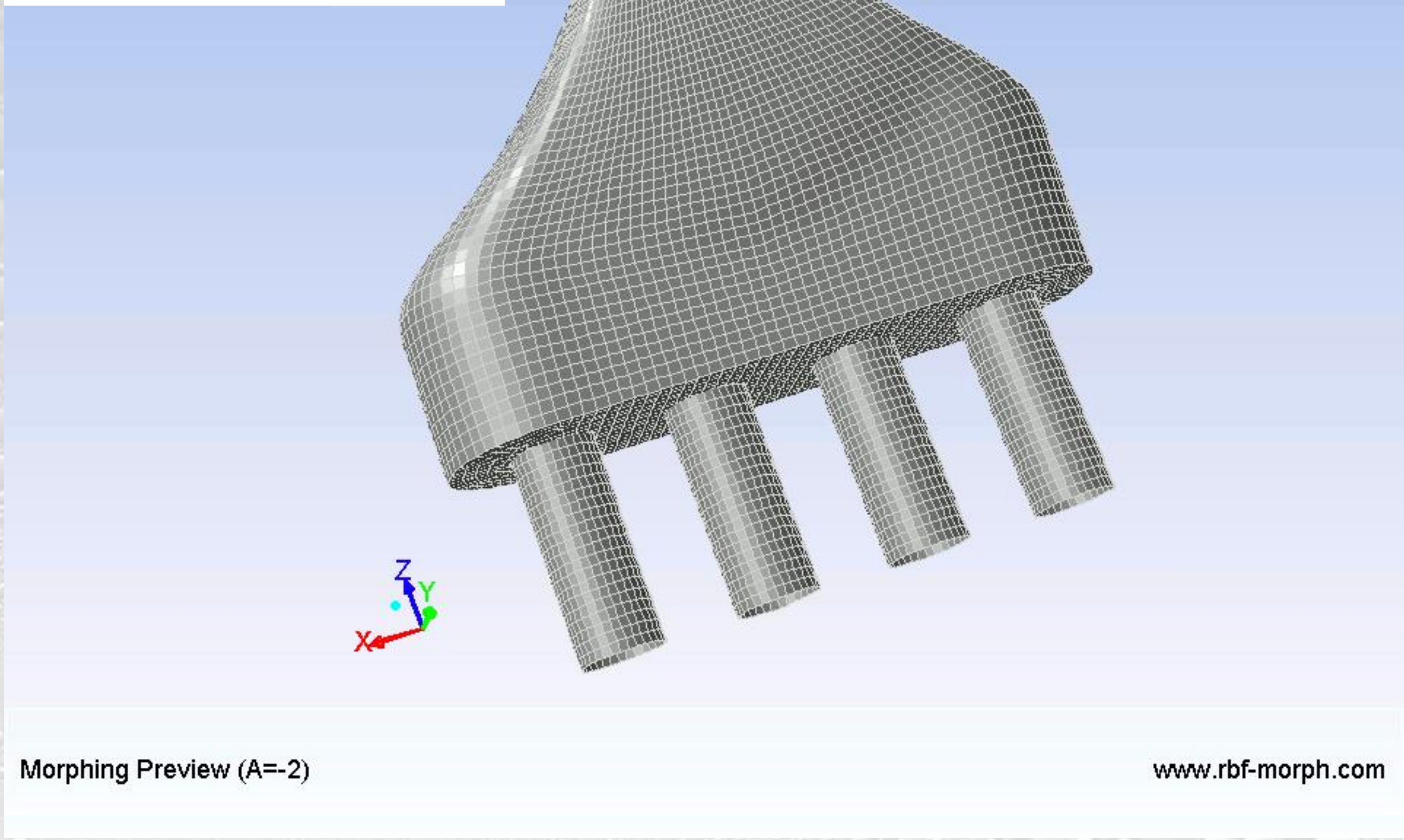
Ship Hull (University of Leeds)



Ship Hull (University of Leeds)

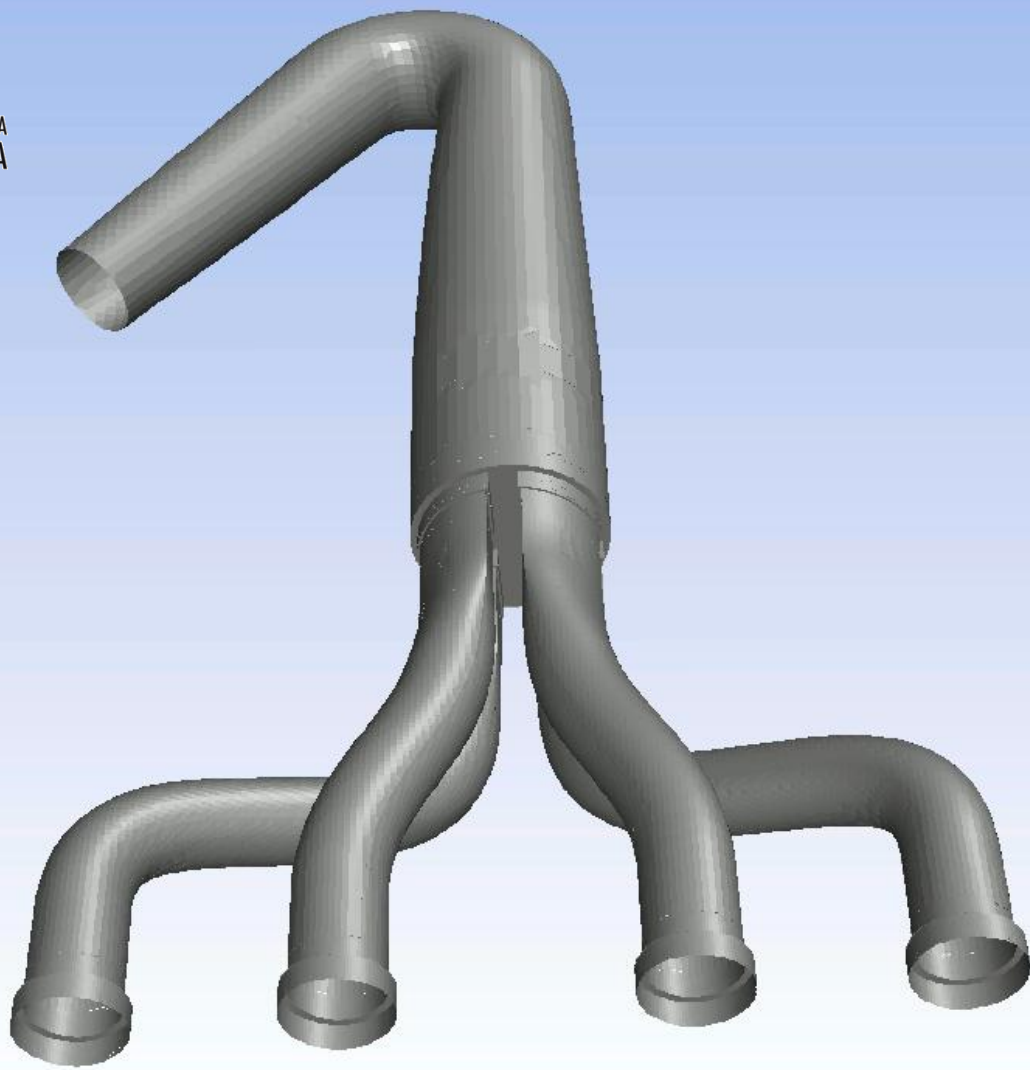
Engine Air box shape (STV FSAE Team)

scuderia tor vergata



Exhaust manifold
Constrained Optimization
Adjoint Solver

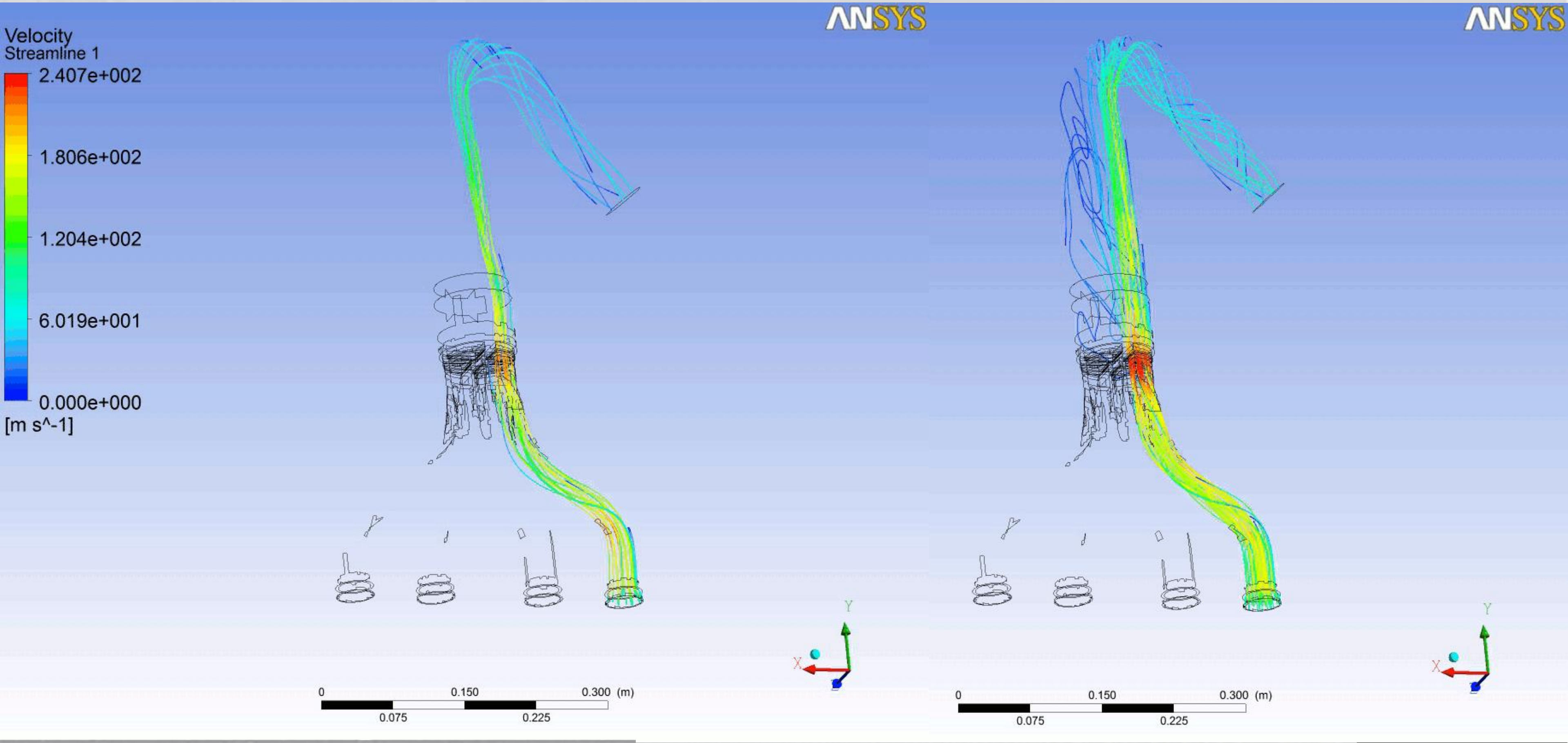
UNIVERSITA' degli STUDI di ROMA
TOR VERGATA



A	B	C	D	E	F	G	H	I
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

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

Optimized vs. Original - Streamlines

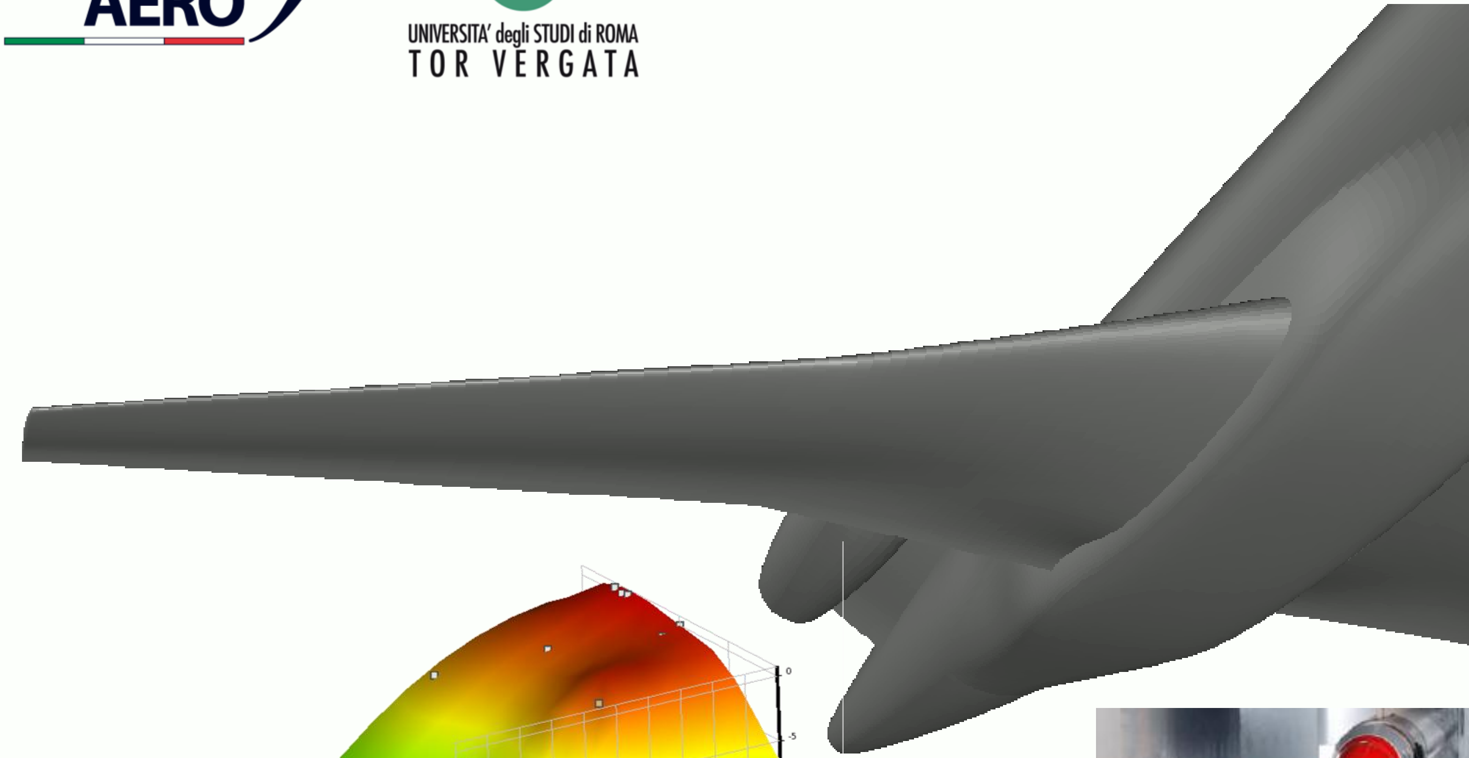


Optimization of sweep angles (Piaggio Aero Industries)

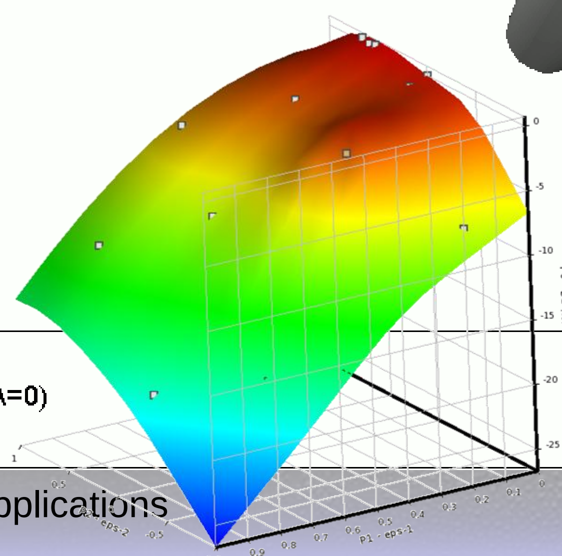
PIAGGIO AERO

UNIVERSITA' degli STUDI di ROMA TOR VERGATA

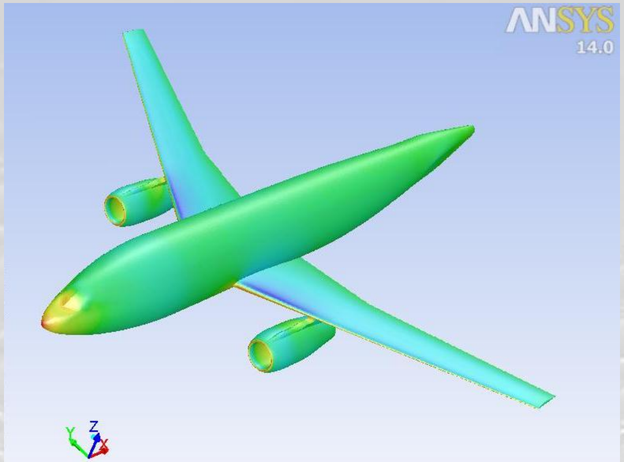
ANSYS 14.0

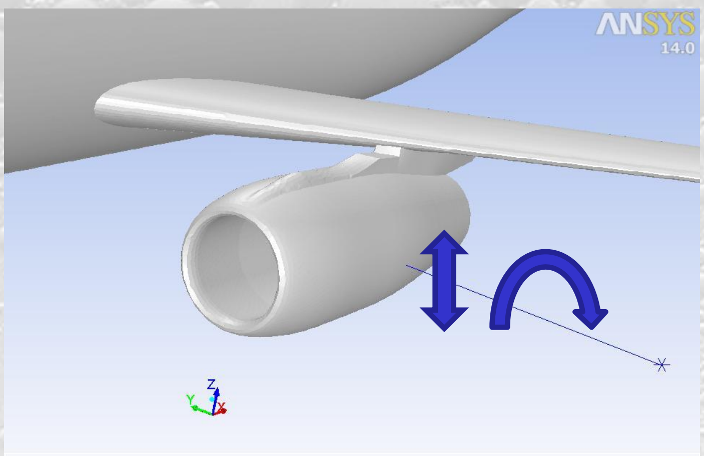


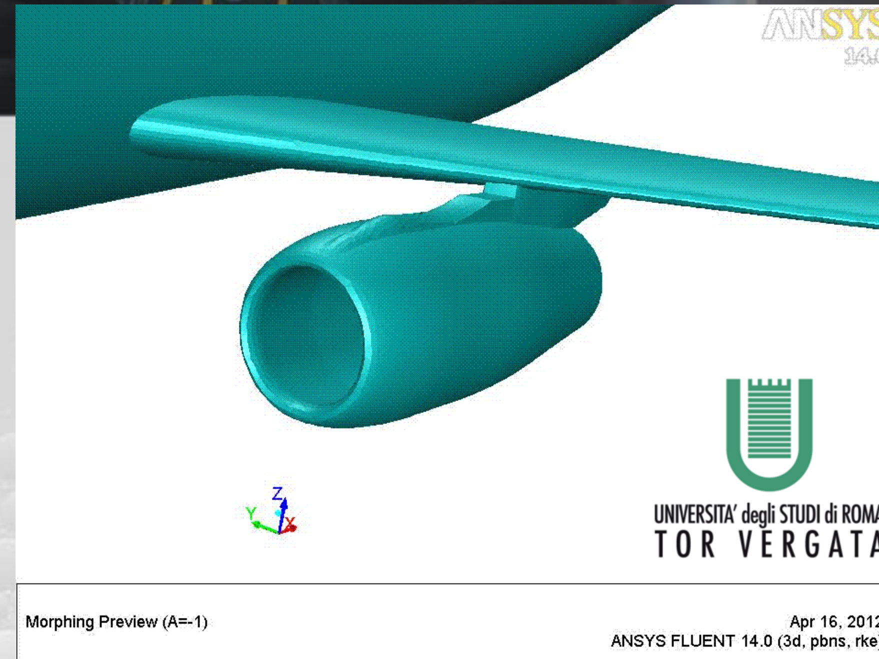
Morphing Preview (A=0)

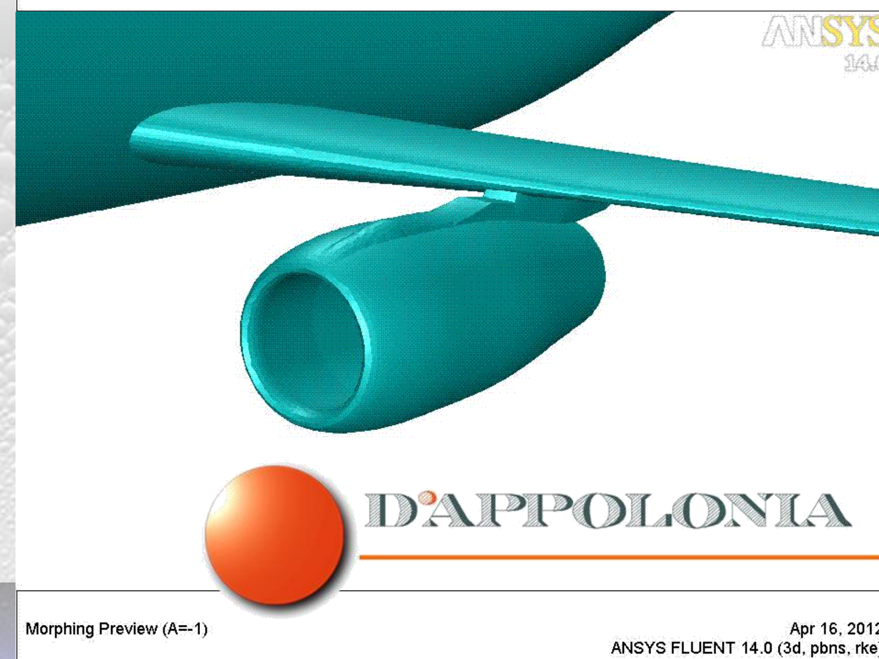


Optimization of nacelle (D'Appolonia)









EU Project RBF4AERO – FP7Transport

- *“Innovative Benchmark Technology for Aircraft Engineering Design and Efficient Design Phase Optimisation”* – **GA no. ACP3-GA-2013-605396**
- **www.rbf4aero.eu**

RBF4AERO

MIRA Reference car
(MIRA ltd)

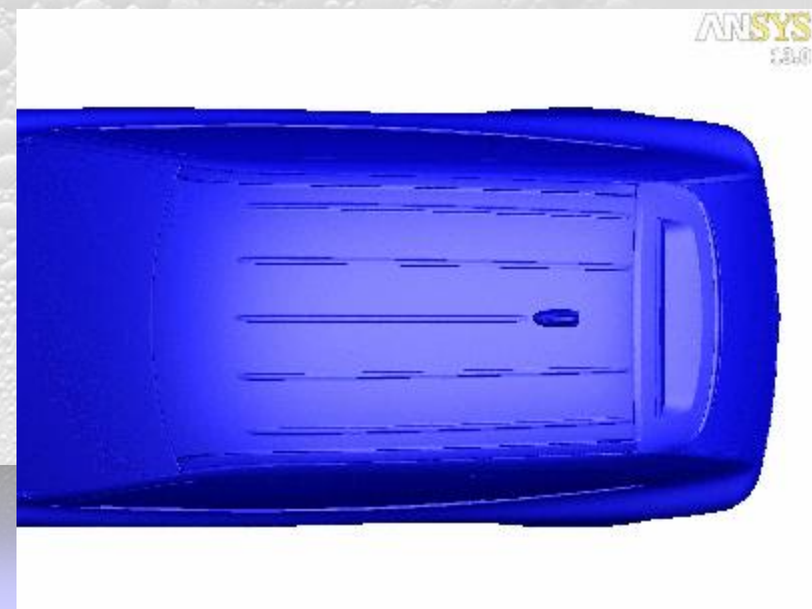
MIRA

MIRA Reference Car

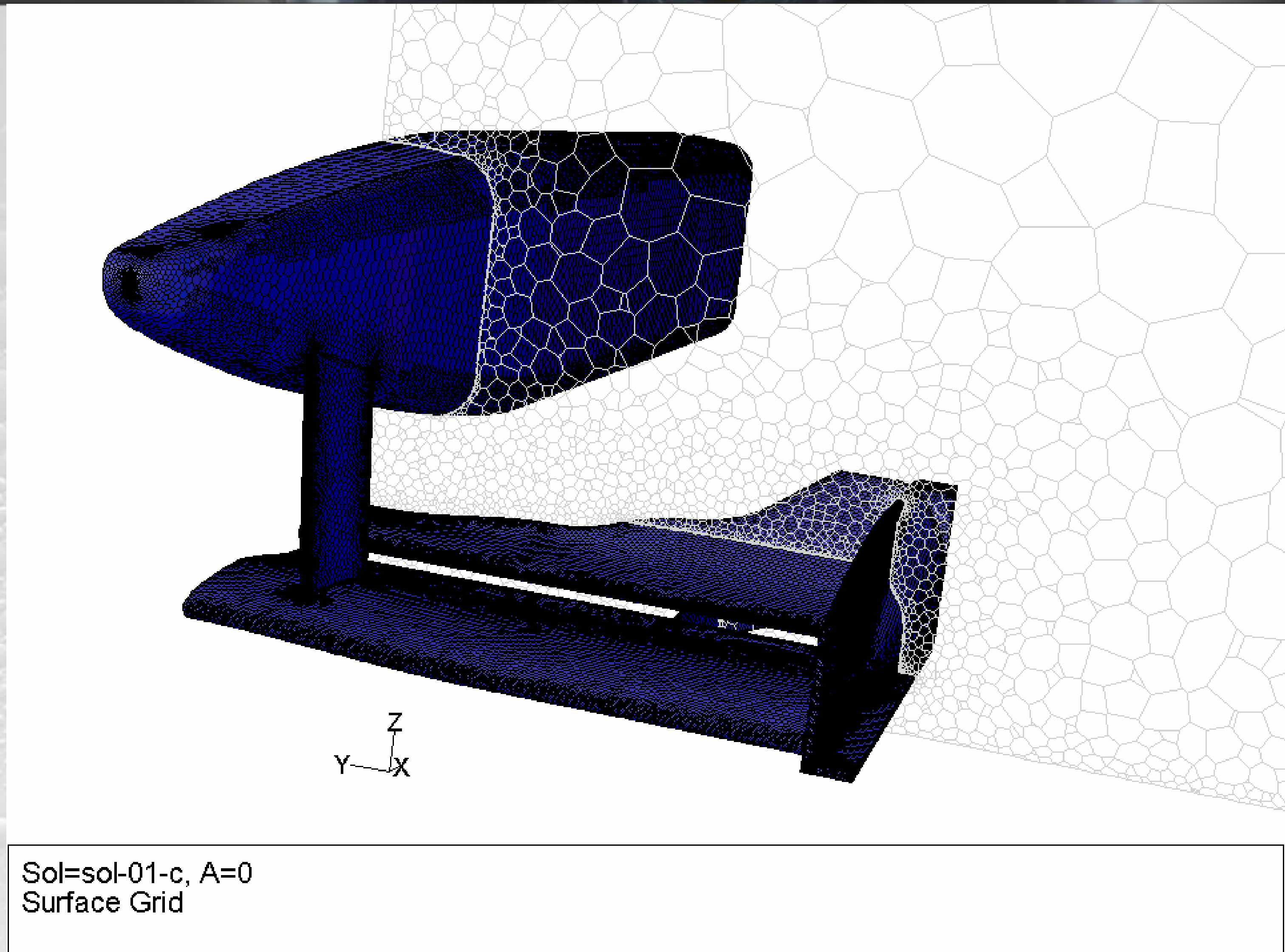
Shape Optimisation using RBF-Morph

Smarter Thinking.

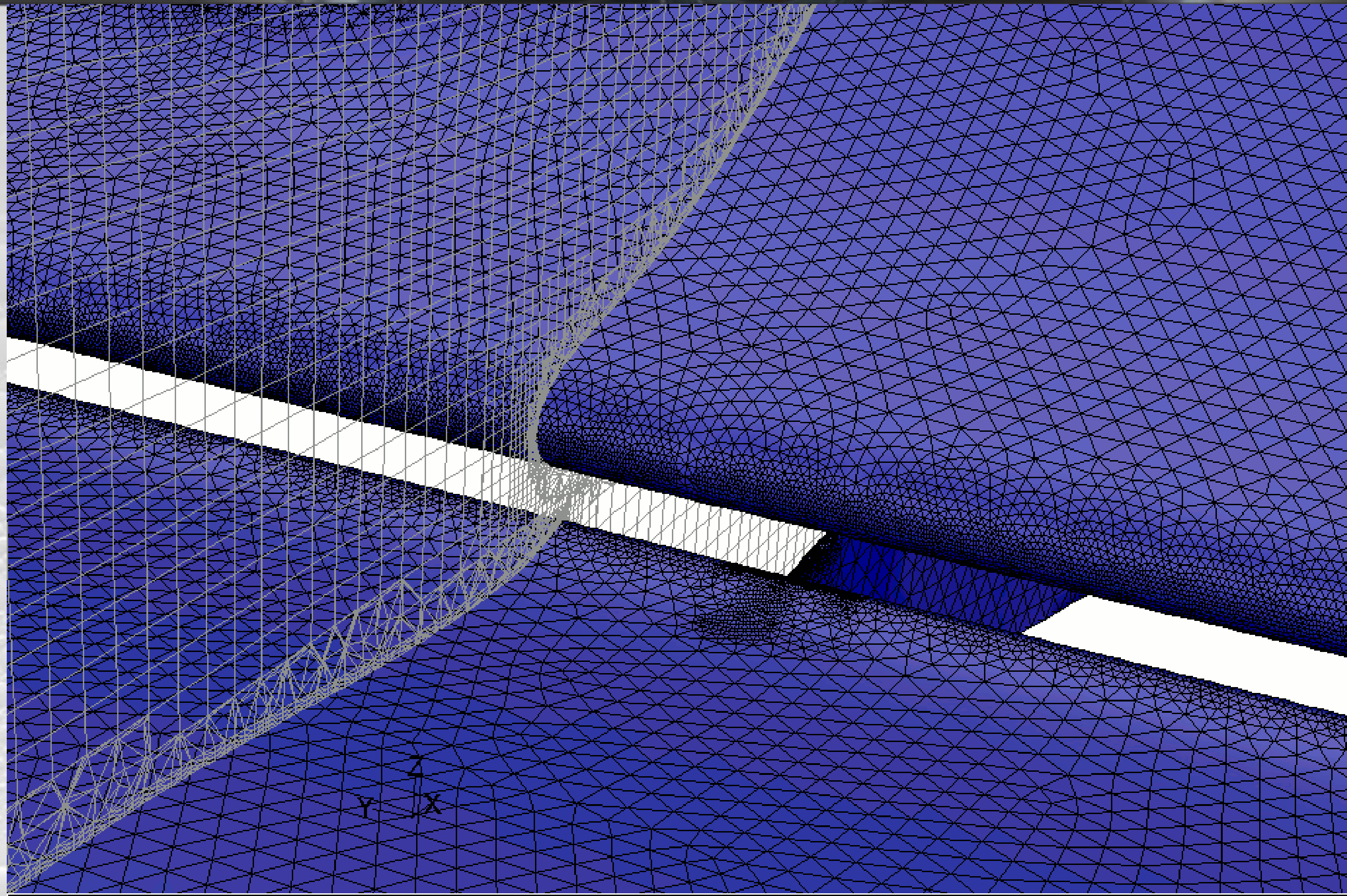
50:50:50 Project Volvo XC60 (Ansys, Intel, Volvo)



Generic Formula 1 Front End



Generic Formula 1 Front End



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

MORPH lab

LET'S PLAY TOGETHER!

Tor Vergata

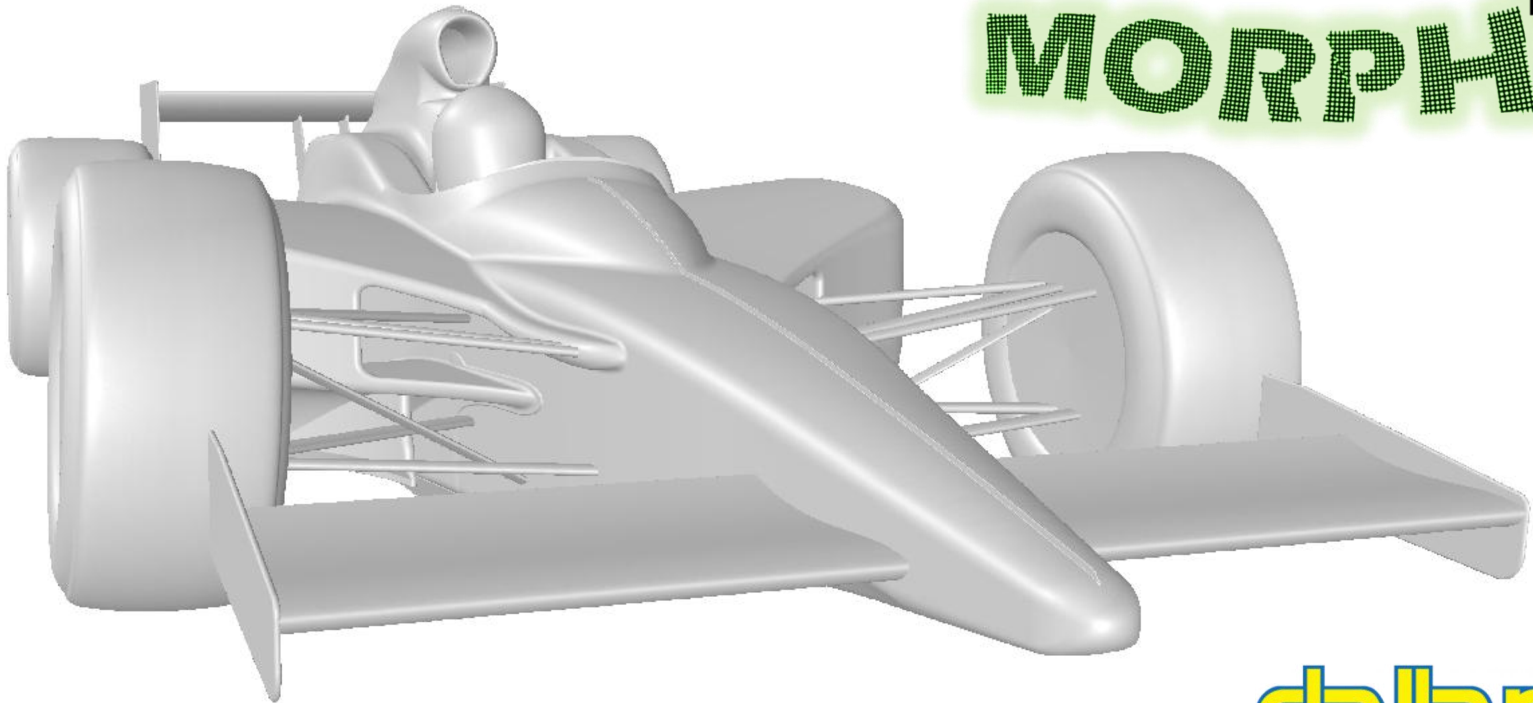
What is MorphLab?

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.

MORPH lab



dallara

ANSYS FLUENT

hp

NVIDIA

PIAGGIO AERO

(rbf-morph)™

CINECA SCAI
SuperComputing Applications and Innovation

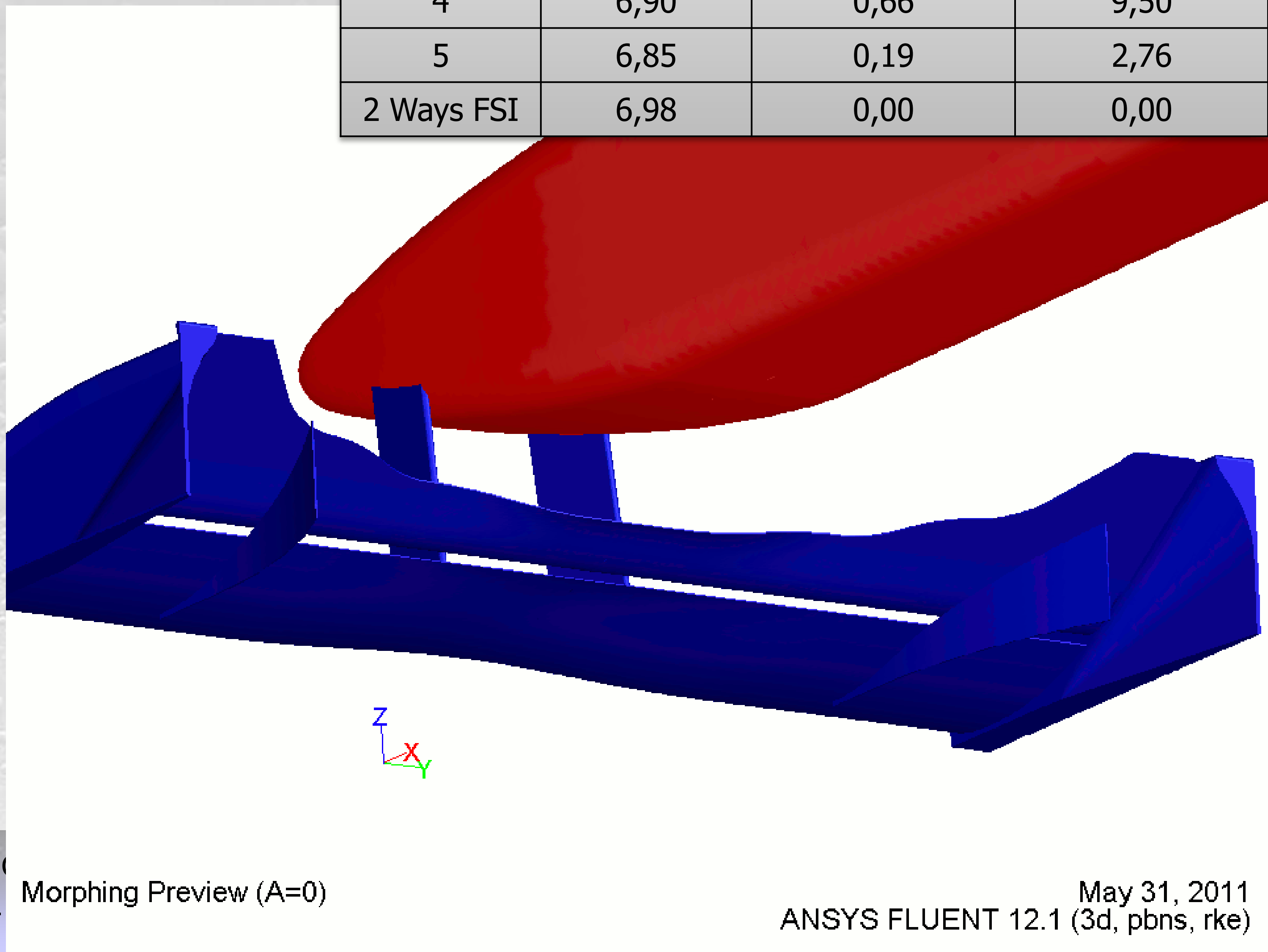
D'APPOLONIA

(rbf-morph)™

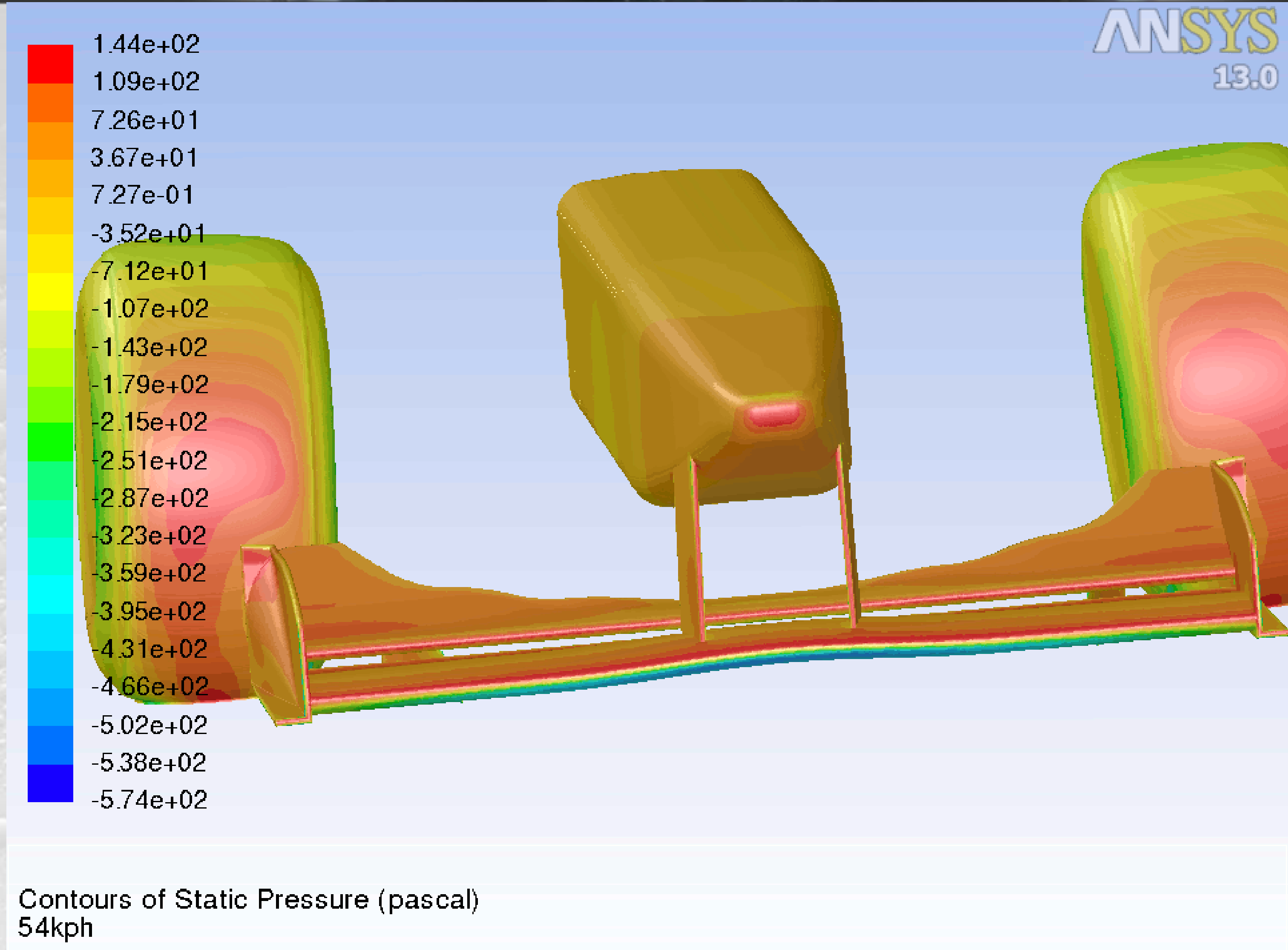
Welcome to the World of Fast Morphing!

Aeroelastic Analysis of Formula 1 Front Wing

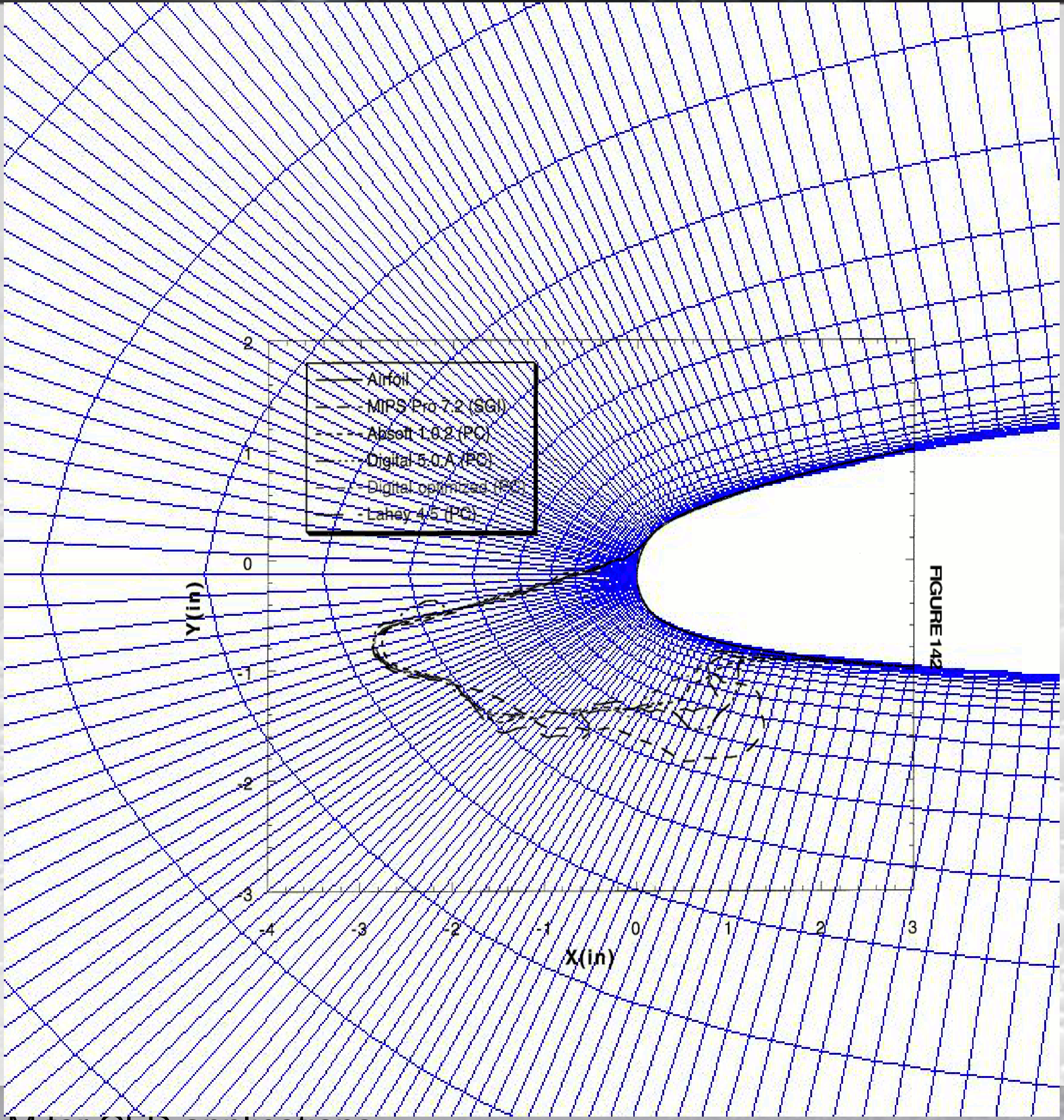
Mode	Disp(mm)	Max err(mm)	Max err (%)
1	7,19	1,61	22,39
2	7,19	0,86	12,00
3	6,98	0,85	12,15
4	6,90	0,66	9,50
5	6,85	0,19	2,76
2 Ways FSI	6,98	0,00	0,00



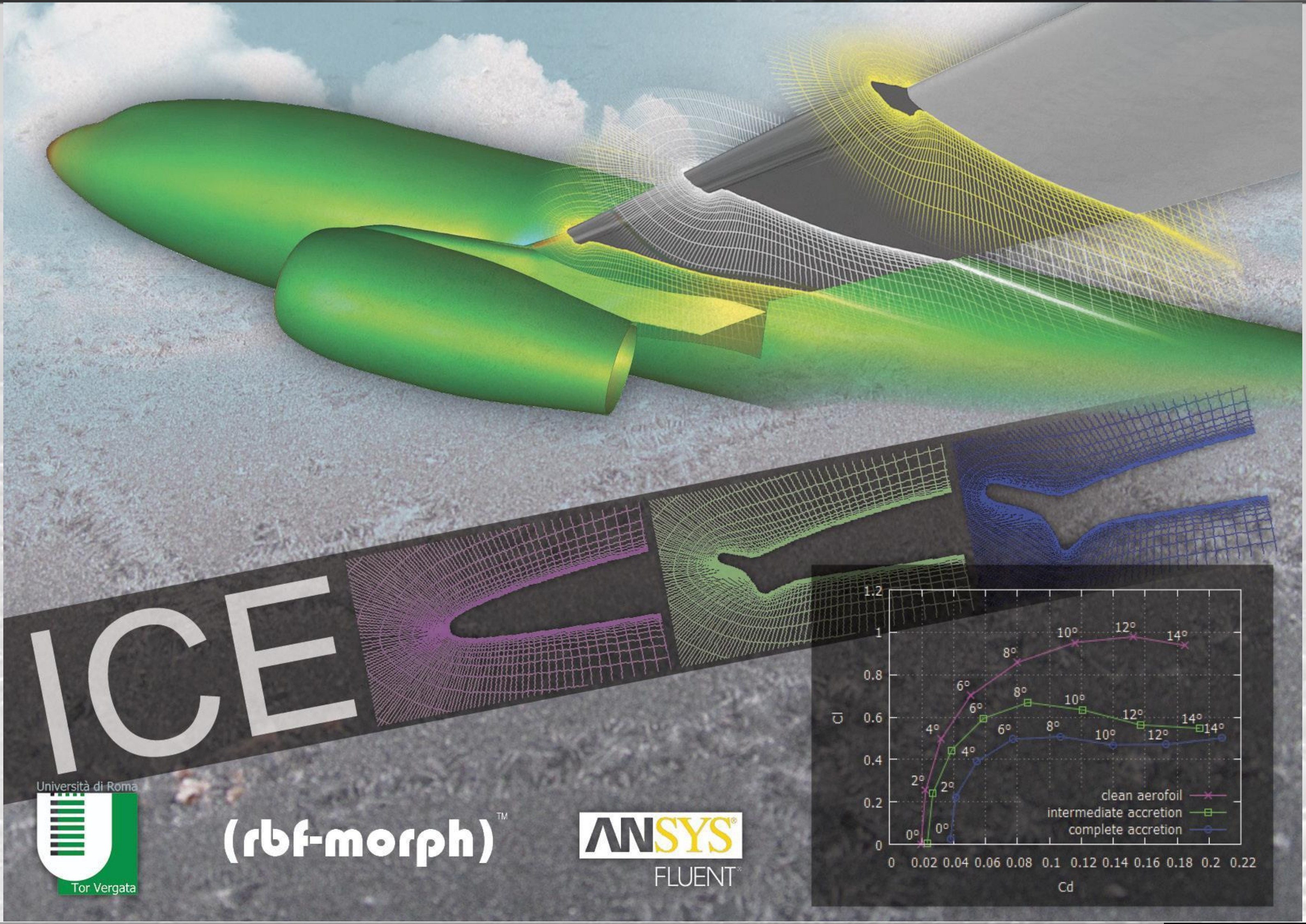
Aeroelastic Analysis of Formula 1 Front Wing



Ice accretion morphing



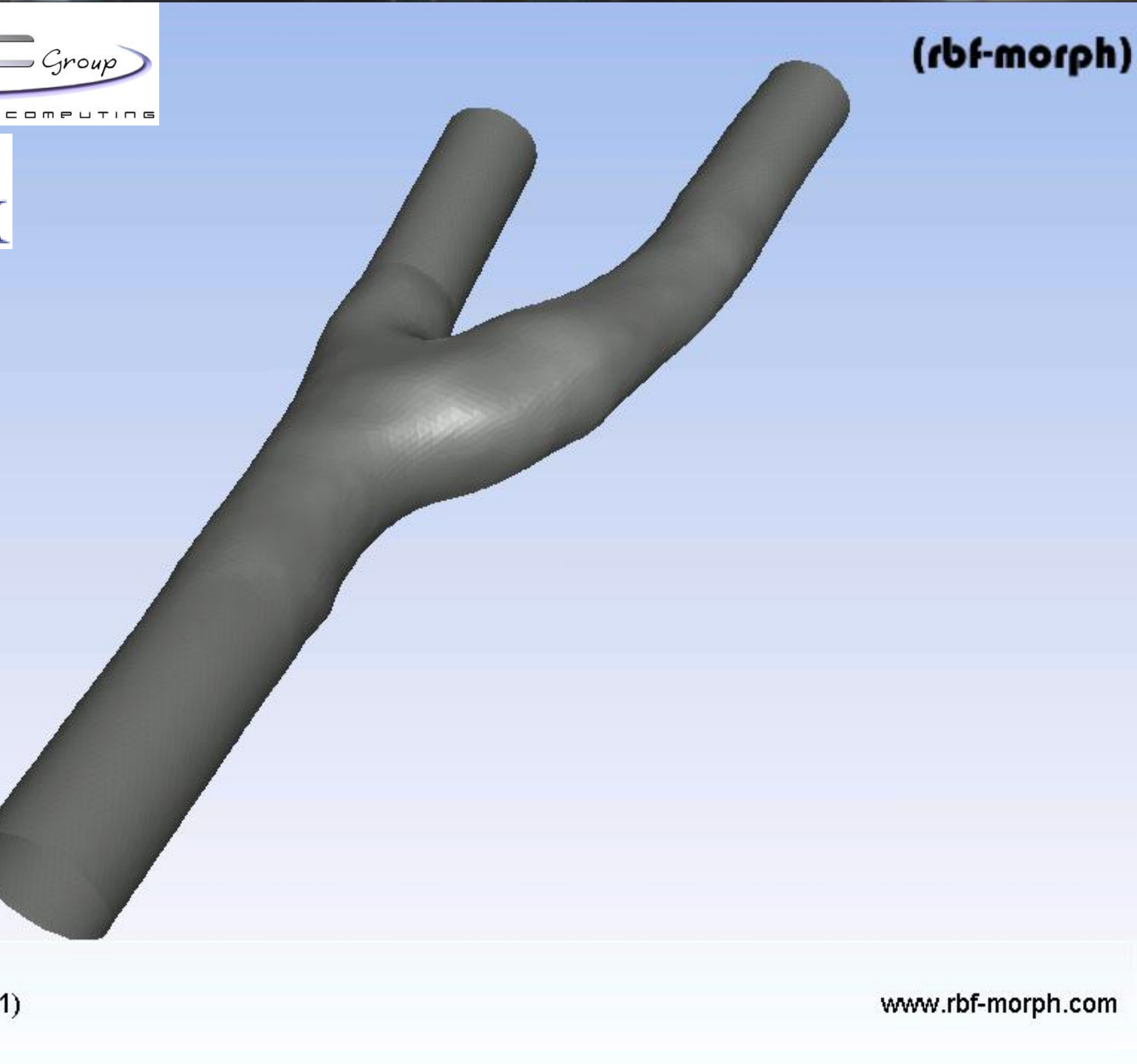
3D accretion morphing



Carotid Bifurcation (Orobix – CILEA)

CILEA HPC Group
HIGH PERFORMANCE COMPUTING

OROBIX



Hands On

Conclusions

- A **shape parametric** CFD model can be defined using ANSYS Fluent and *RBF Morph* – new stand alone tools allow to widen the range of solvers (CFD, FEA) supported by RBF Morph technology.
- **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
- Local mesh control allows to enable multi-physics as well (FSI, Icing, adjoint)
- ***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/).

Thank you for your attention!

Dr. Marco Evangelos Biancolini

E-mail: info@rbf-morph.com
Web: www.rbf-morph.com
YouTube: www.youtube.com/user/RbfMorph