RBF Morph

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Tor Vergata

PRACE Autumn School 2013 - Industry Oriented HPC Simulations, September 21-27, University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia

RBF Morph Training Agenda

Session #1

General Introduction of RBF Morph, Features with examples

Session #2

Basic Usage of RBF Morph, Examples and Live demonstration

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)*

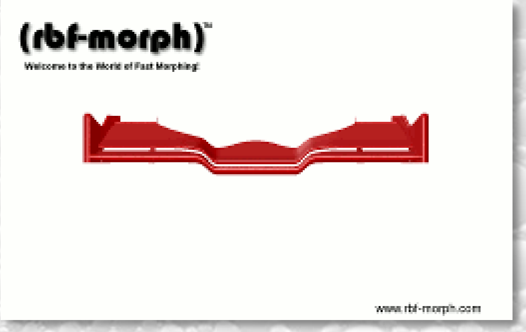
Linkedin: http://it.linkedin.com/in/marcobiancolini

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

RBF Morph Training

General Introduction of RBF Morph, Features with examples

Dr. Marco Evangelos Biancolini


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

Outline

- RBF Morph tool presentation
- Industrial Applications
- Modelling Guidelines

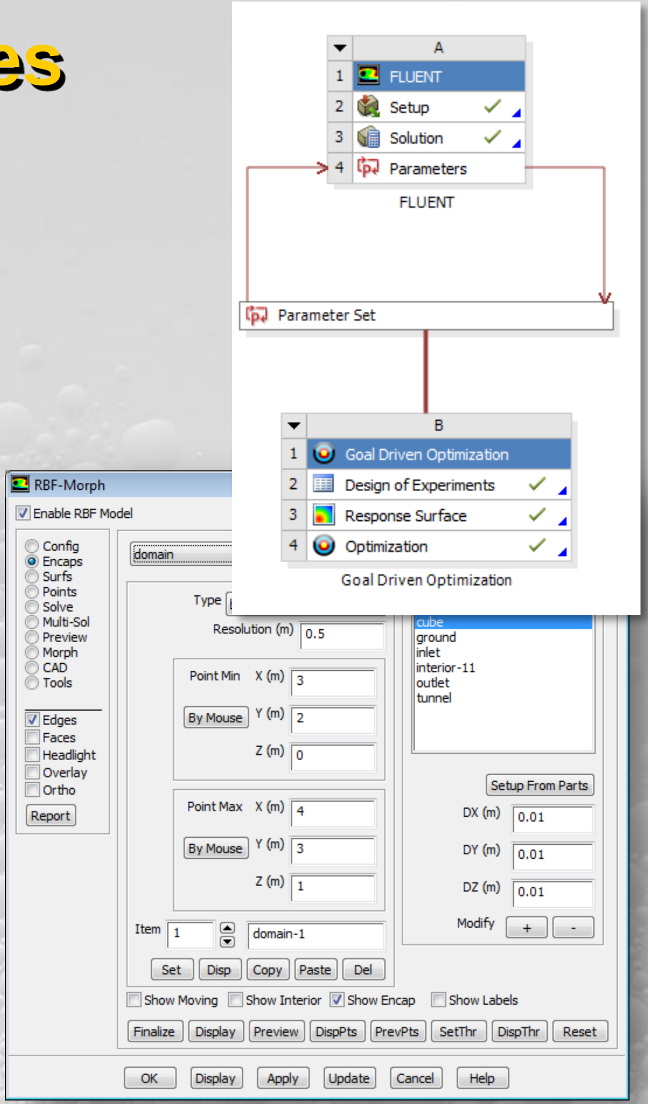
RBF Morph tool presentation

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**).



☑ Enable RBF Model

domain

Type

Resolution (m) 0.5

Point Min X (m) 3
Y (m) 2
Z (m) 0

Point Max X (m) 4
Y (m) 3
Z (m) 1

Item 1 domain-1

DX (m) 0.01
DY (m) 0.01
DZ (m) 0.01

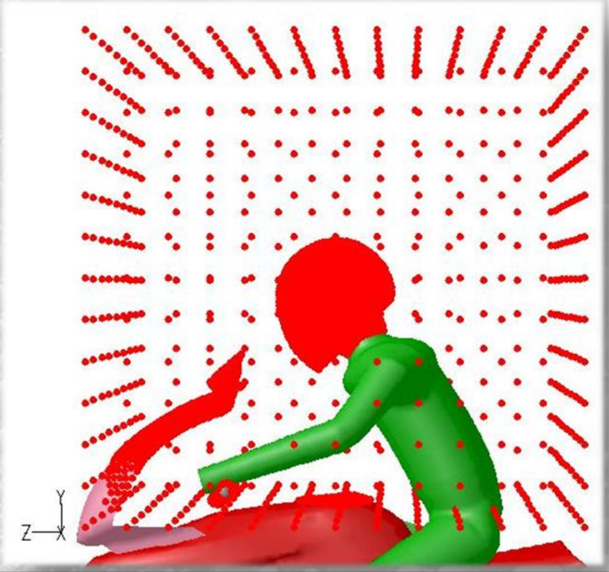
☑ Edges
☐ Faces
☐ Headlight
☐ Overlay
☐ Ortho

☐ Show Moving ☐ Show Interior ☑ Show Encap ☐ Show Labels

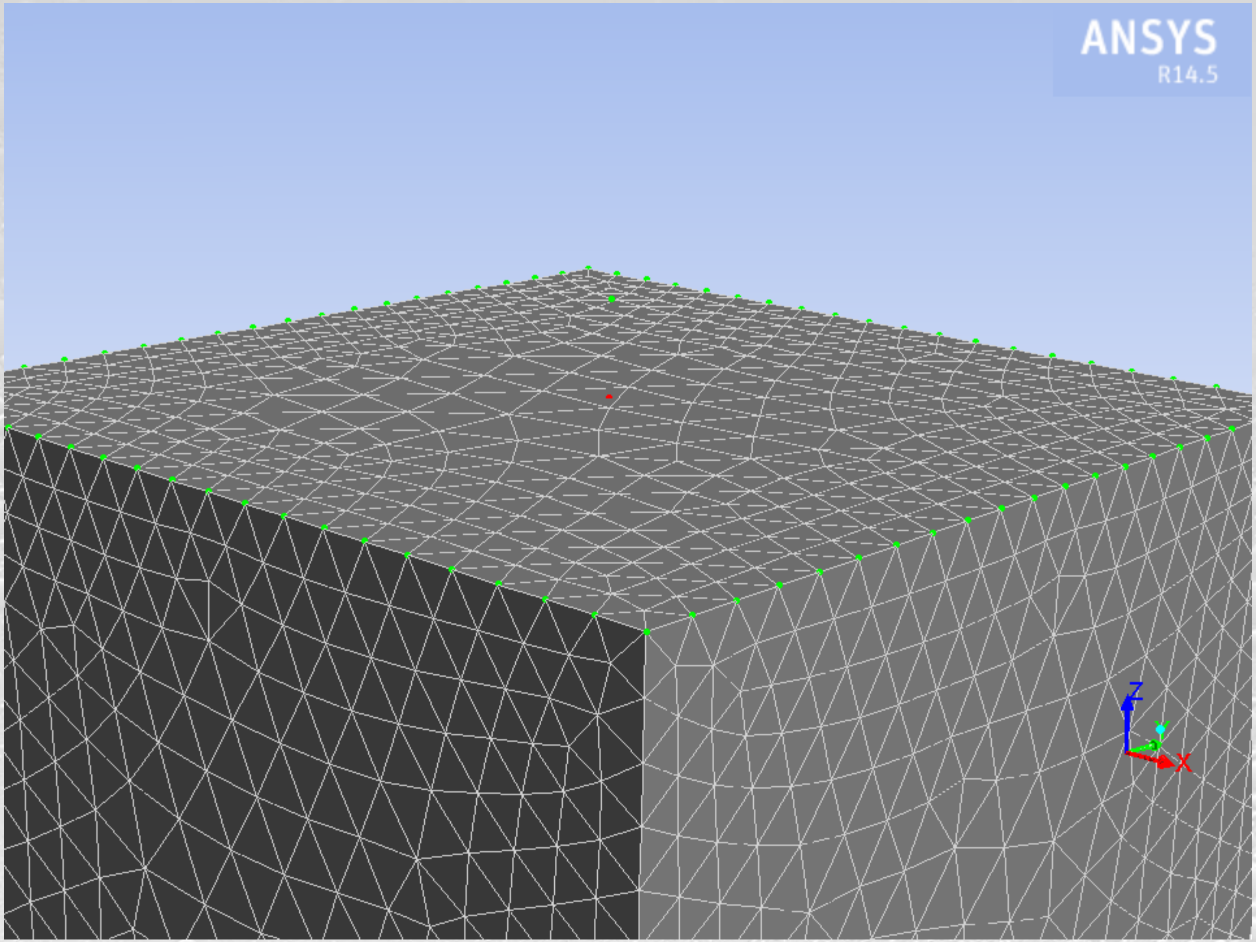
Mesh Morphing with Radial Basis Functions

- 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:

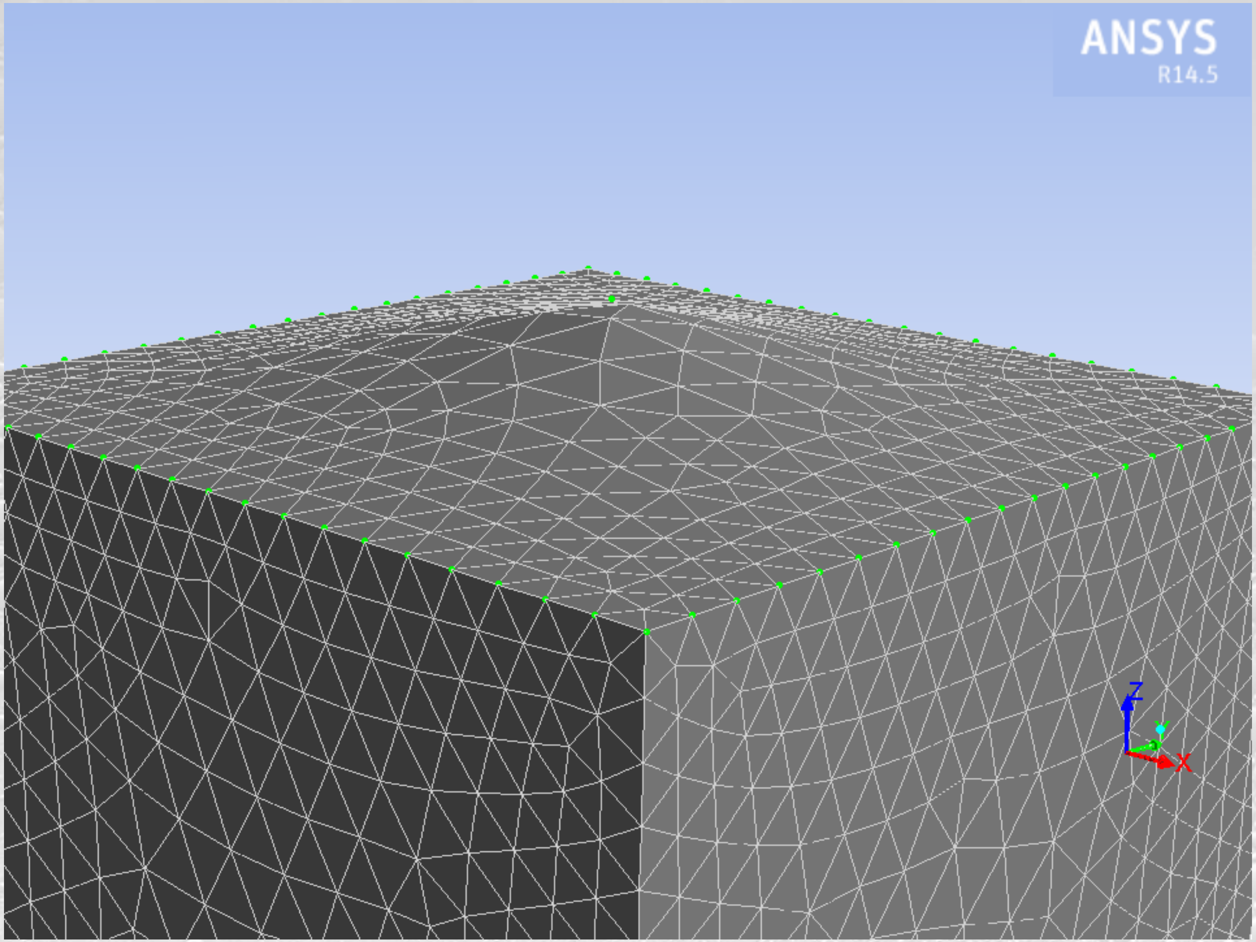
$$\begin{cases} v_x = s_x(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^x \phi\left(\left\|\mathbf{x} - \mathbf{x}_{k_i}\right\|\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ v_y = s_y(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^y \phi\left(\left\|\mathbf{x} - \mathbf{x}_{k_i}\right\|\right) + \beta_1^y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



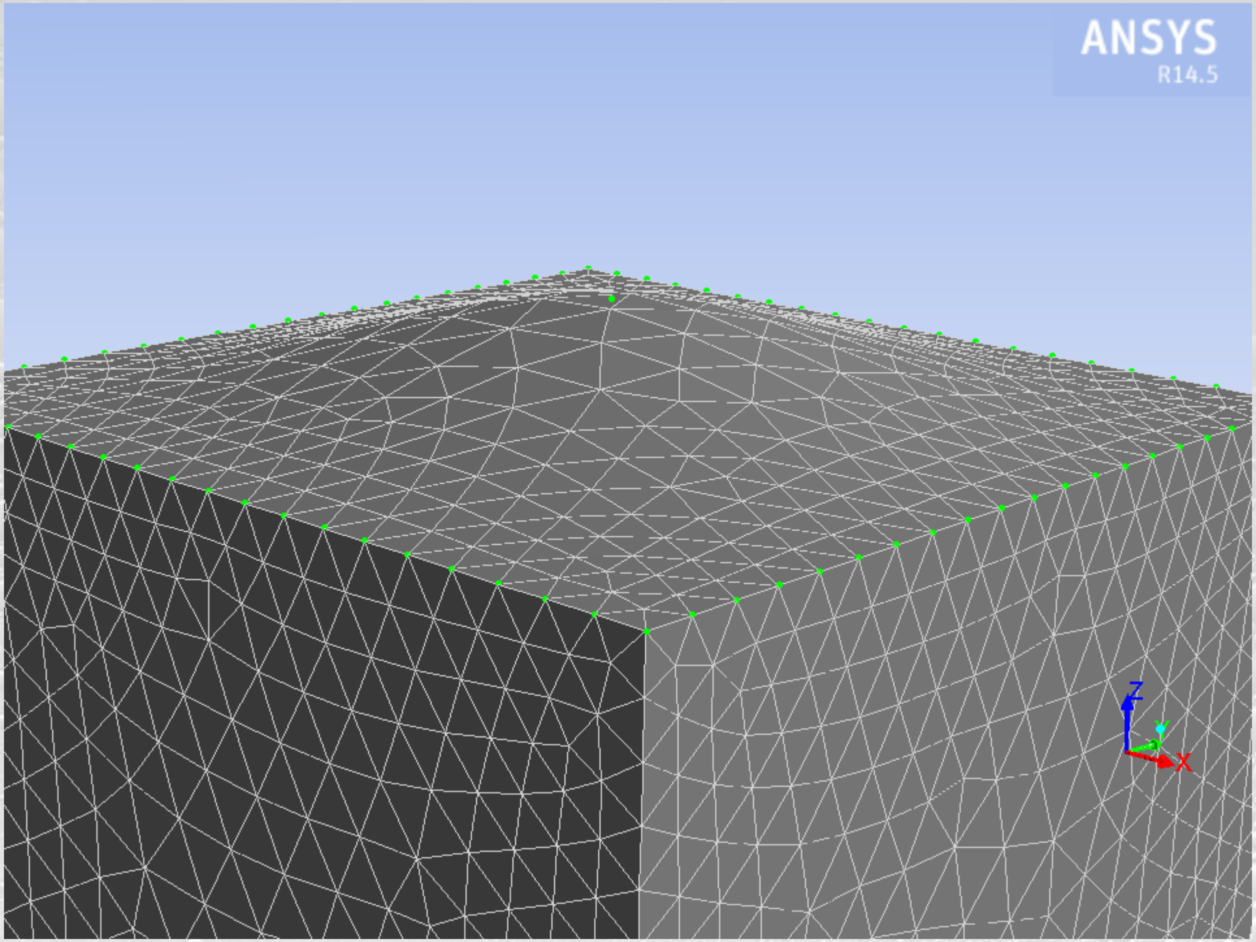
One pt at center 80 pts at border



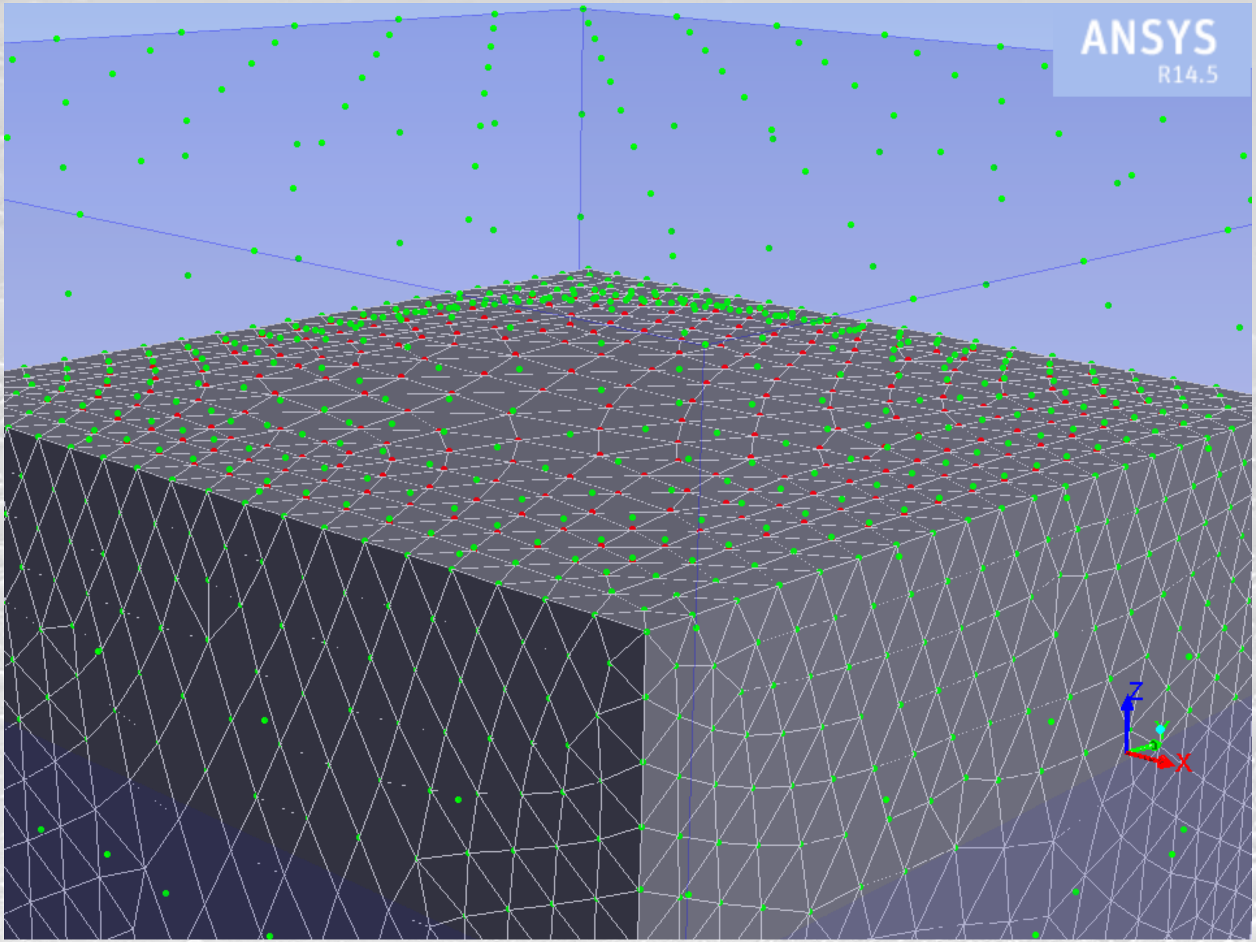
Effect on surface (gs-r)



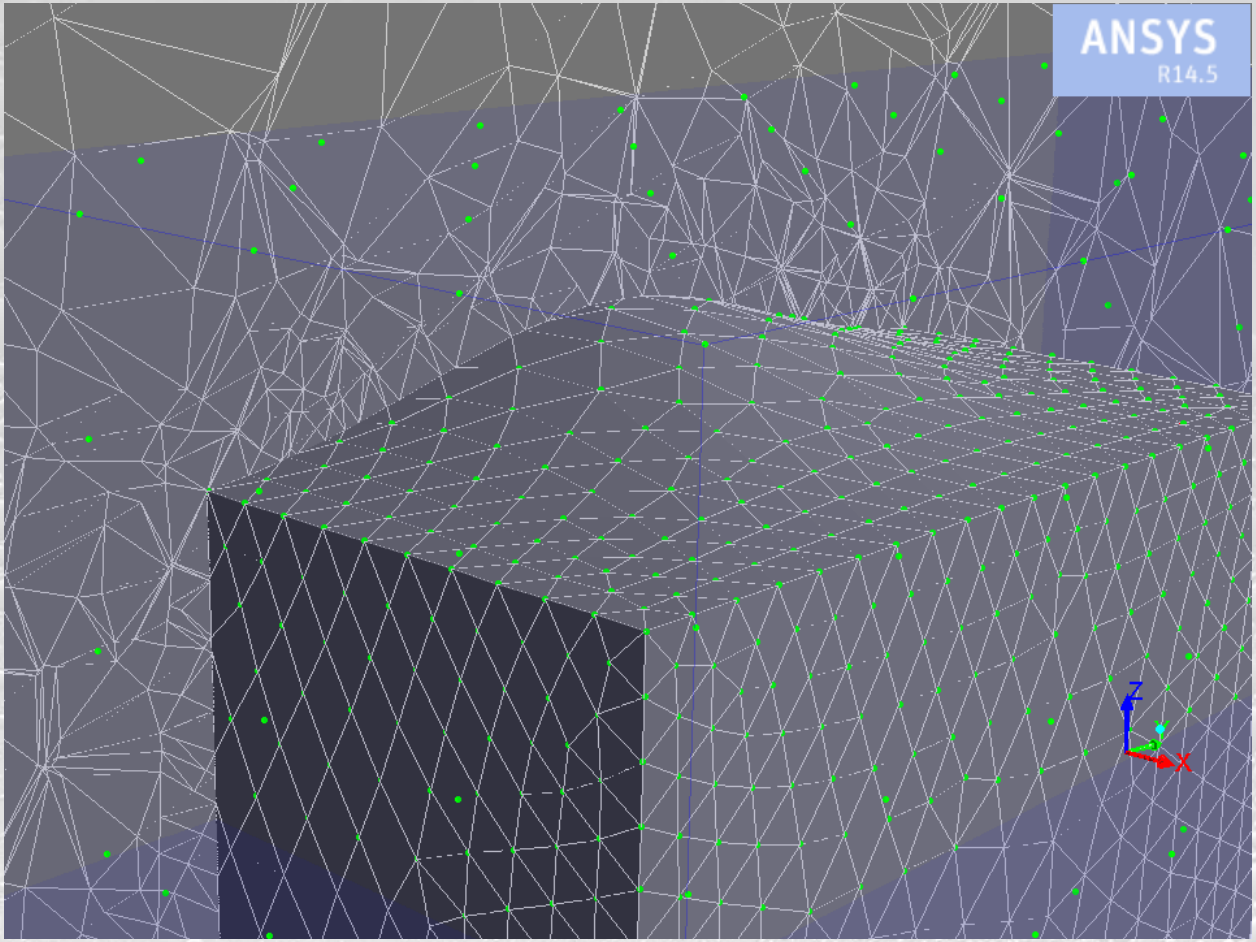
Effect on surface (cp-c4)



Control of volume mesh (1166 pts)



Morphing the volume mesh



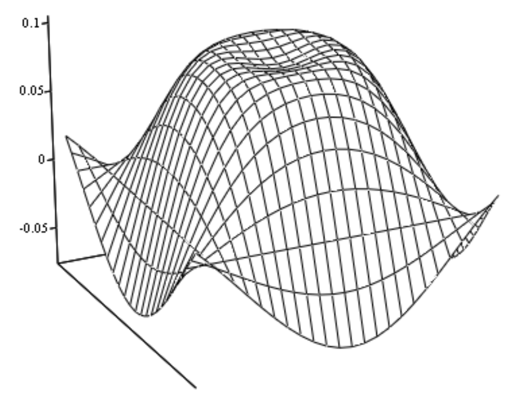
Background: RBF Theory

- 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.



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

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

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)	$\|r\|^n$, n odd
Thin plate spline (TPS_n)	$\|r\|^n \log\|r\|$, 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 **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 **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 $^{1.87}$

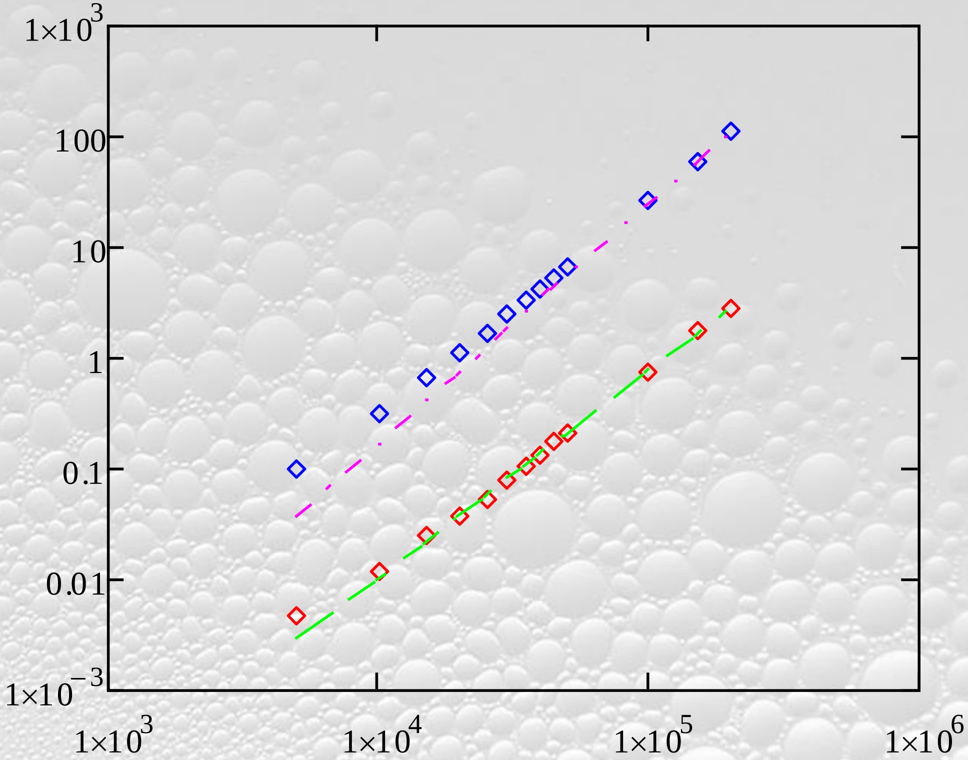
- CPU observed as

N $^{2.174}$

- Estimation at one million points:

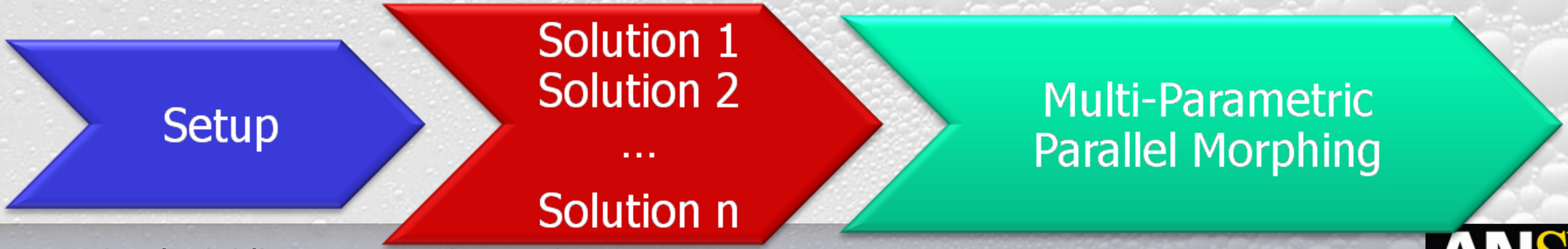
GPU: 59 s

CPU: 2783 s



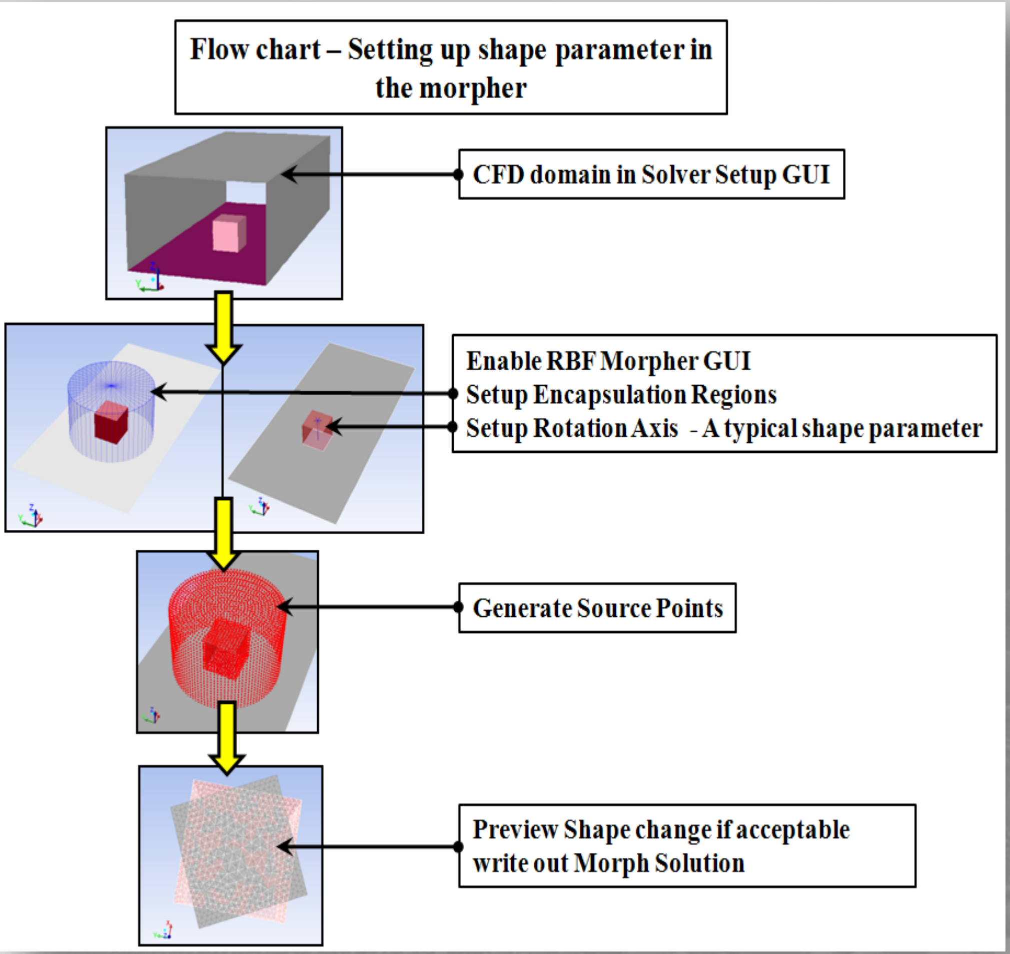
How it Works: the work-flow

- *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**.



Flow chart – Setting up shape parameter in the morpher

CFD domain in Solver Setup GUI

Enable RBF Morpher GUI
Setup Encapsulation Regions
Setup Rotation Axis - A typical shape parameter

Generate Source Points

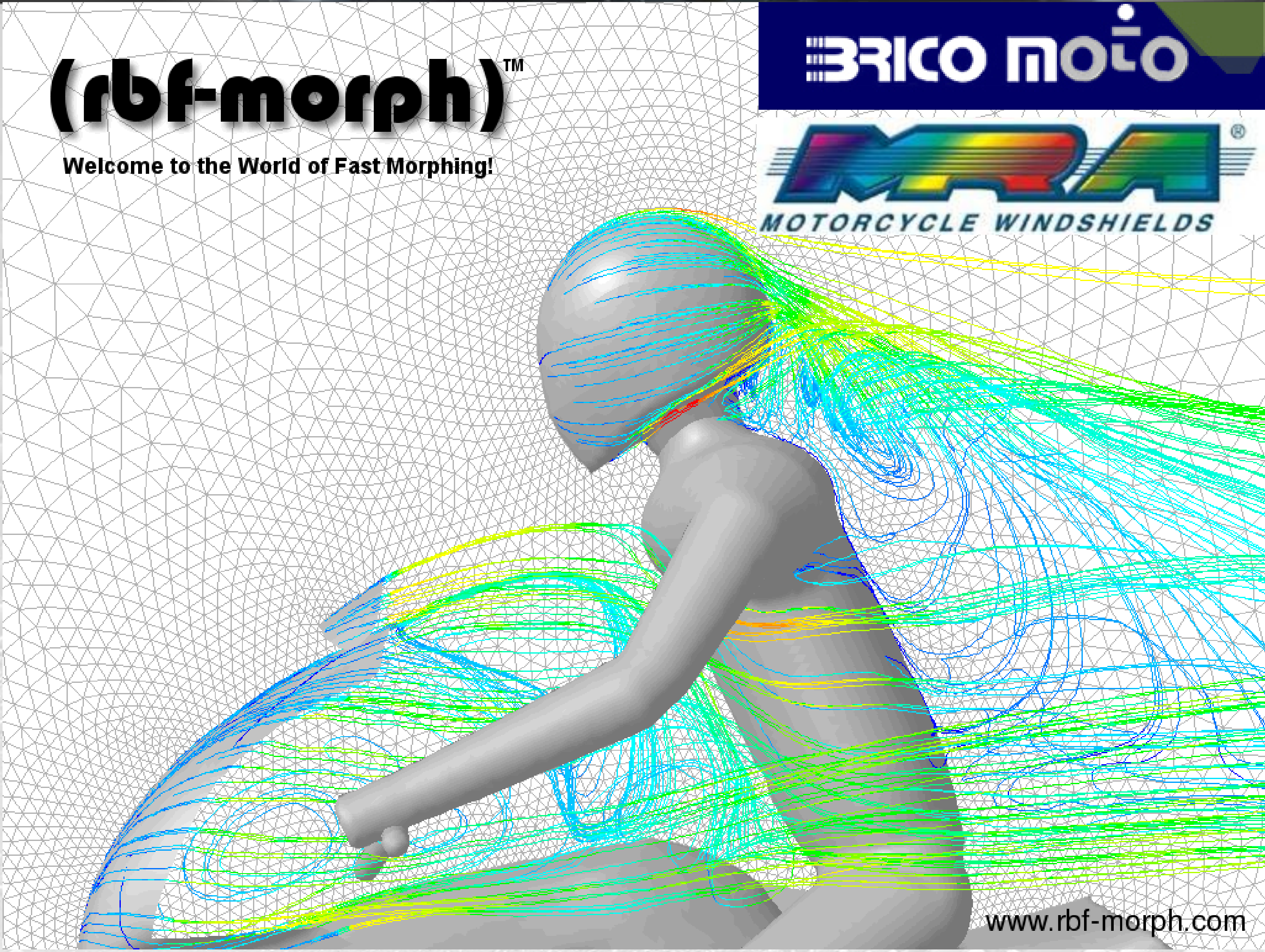
Preview Shape change if acceptable
write out Morph Solution

How it Works: 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 …)

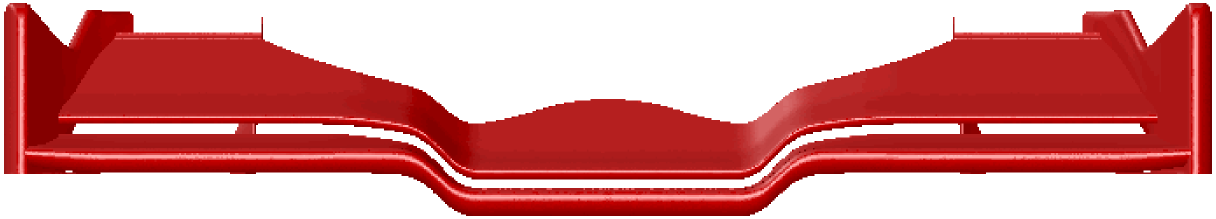
Industrial Applications

Motorbike Windshield (Bricomoto, MRA)



Formula 1 Front Wing

Welcome to the World of Fast Morphing!



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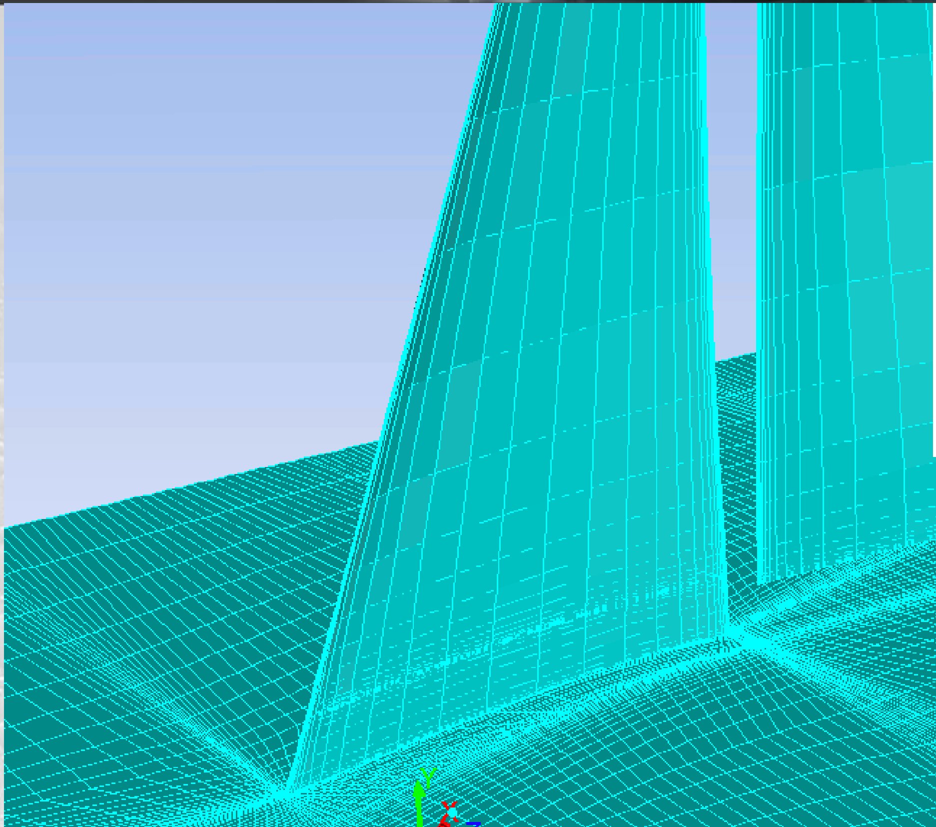
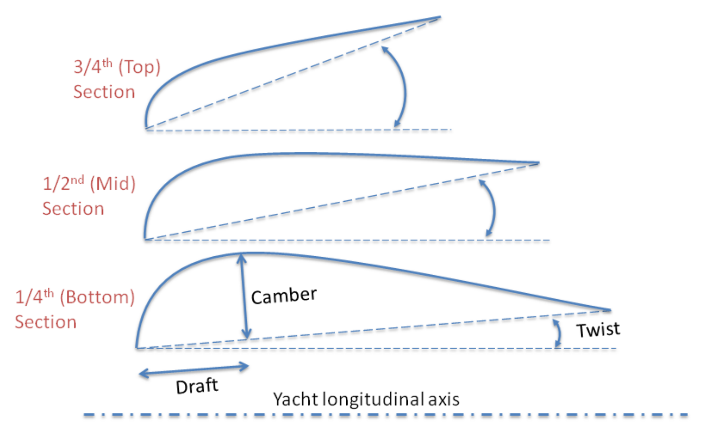
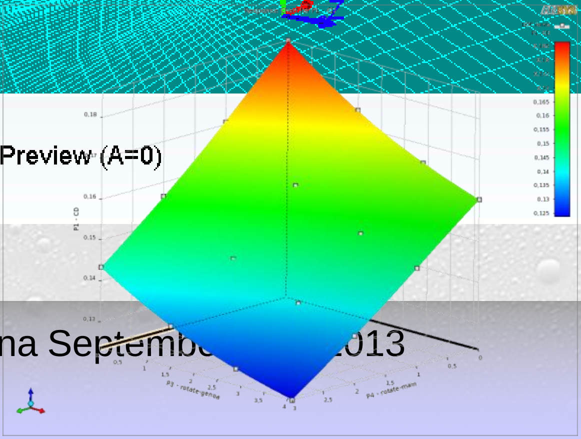
Sails Trim (Ignazio Maria Viola, University of Newcastle)





Morphing Preview (A=0)



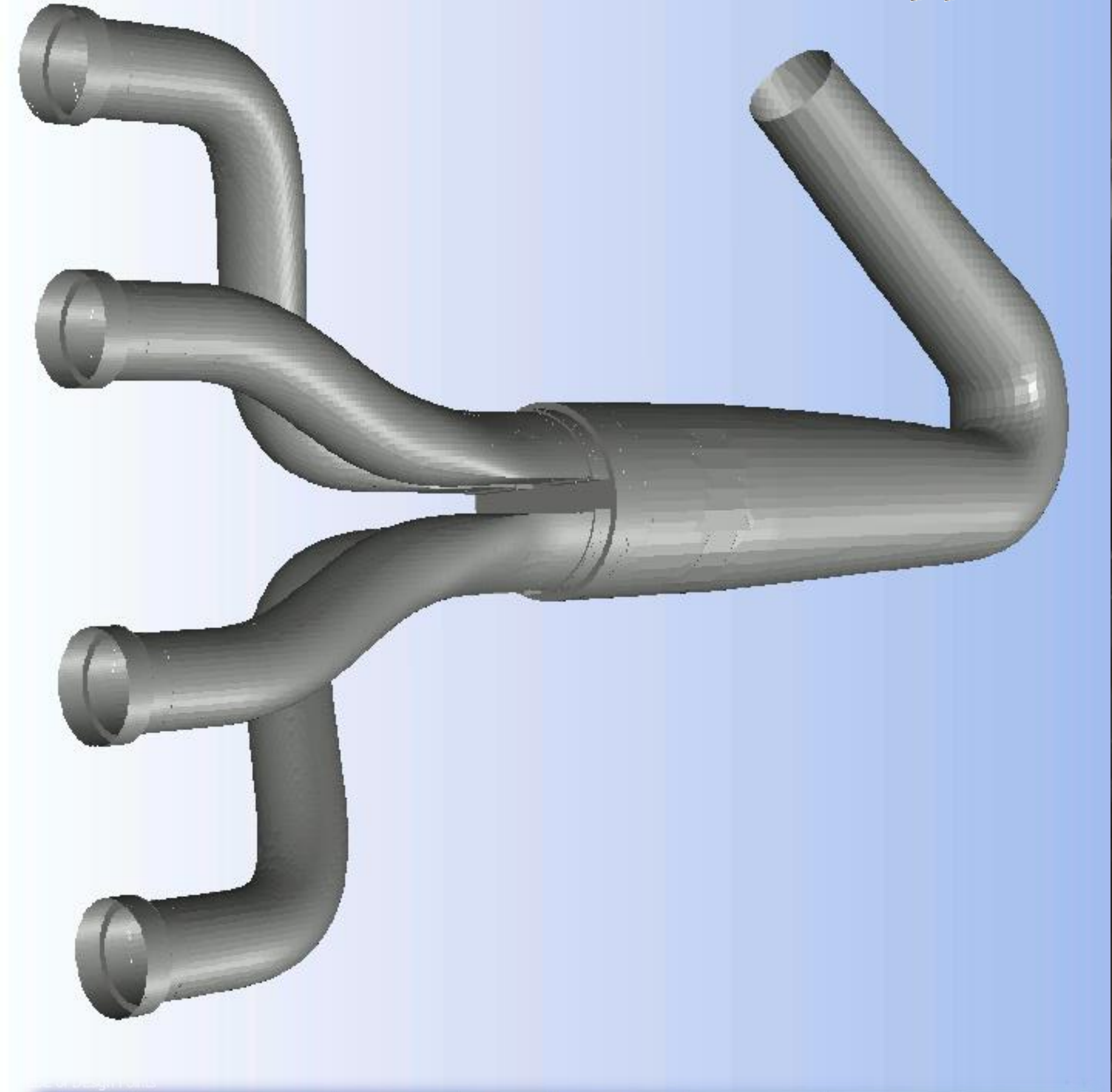
Yacht and superyacht consultancy and research

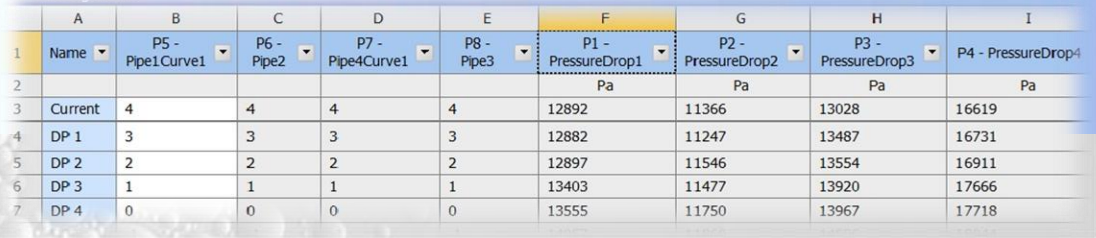
school of marine science and technology

ignazio.viola@ncl.ac.uk

Exhaust manifold Constrained Optimization Adjoint Solver

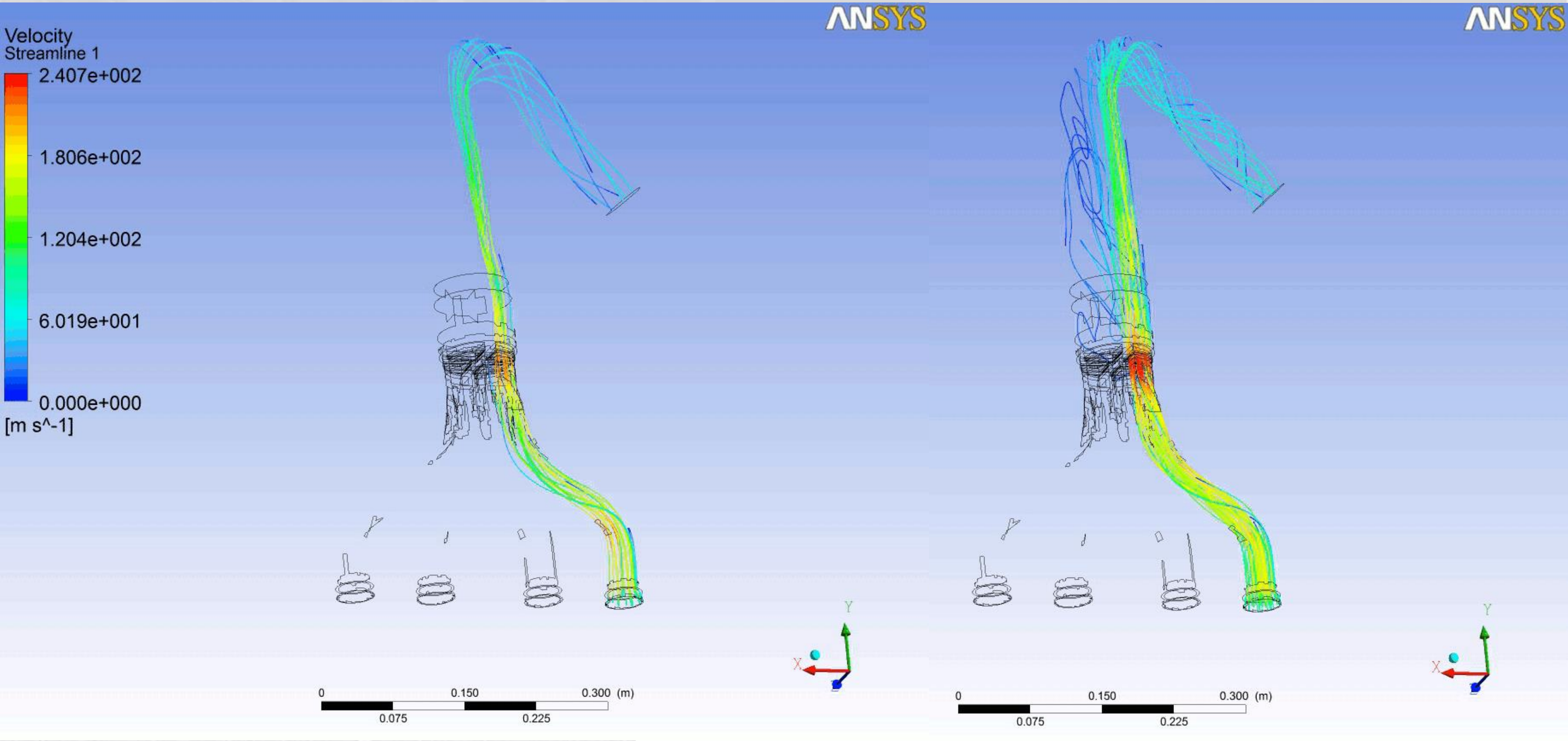
UNIVERSITA' degli STUDI di ROMA
TOR VERGATA





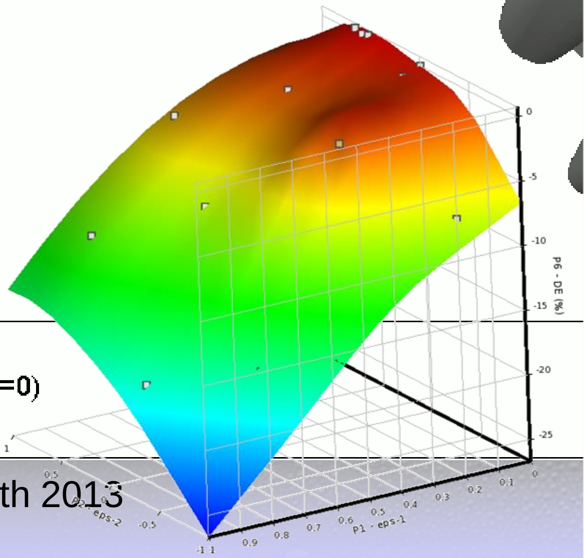
	A	B	C	D	E	F	G	H	I
1	Name	P5 - Pipe1Curve1	P6 - Pipe2	P7 - Pipe4Curve1	P8 - Pipe3	P1 - PressureDrop1	P2 - PressureDrop2	P3 - PressureDrop3	P4 - PressureDrop4
2						Pa	Pa	Pa	Pa
3	Current	4	4	4	4	12892	11366	13028	16619
4	DP 1	3	3	3	3	12882	11247	13487	16731
5	DP 2	2	2	2	2	12897	11546	13554	16911
6	DP 3	1	1	1	1	13403	11477	13920	17666
7	DP 4	0	0	0	0	13555	11750	13967	17718

Optimized vs. Original - Streamlines

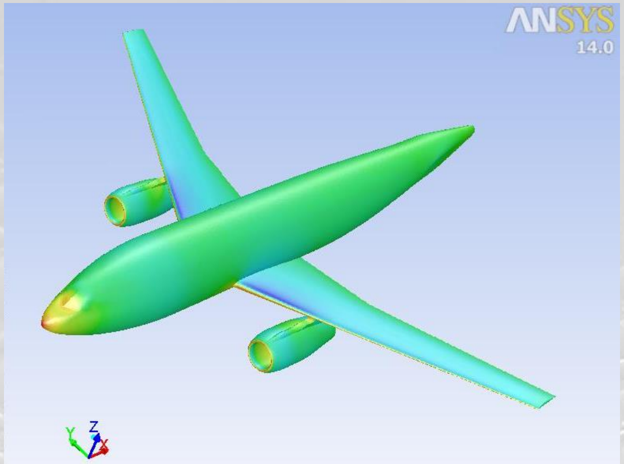


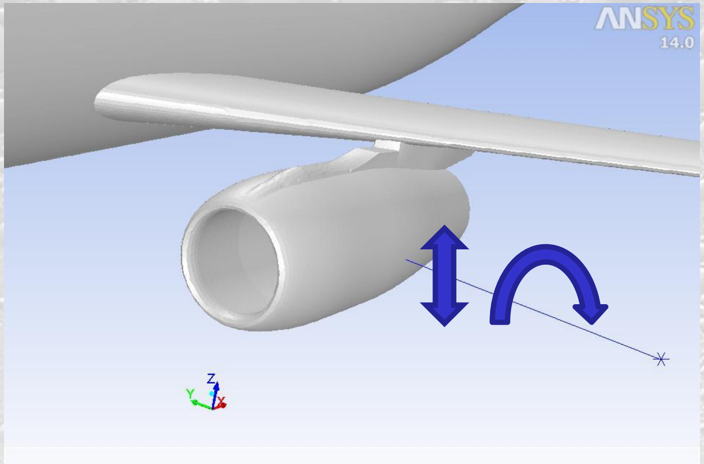
Optimization of sweep angles (Piaggio Aero Industries)

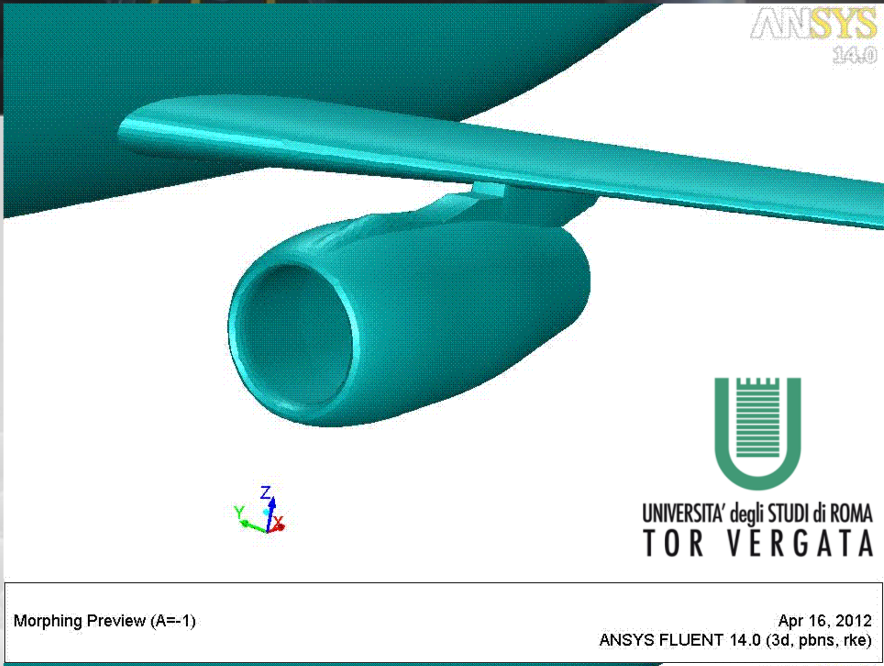
Morphing Preview (A=0)



Optimization of nacelle (D'Appolonia)







Morphing Preview (A=-1)

Apr 16, 2012
ANSYS FLUENT 14.0 (3d, pbns, rke)

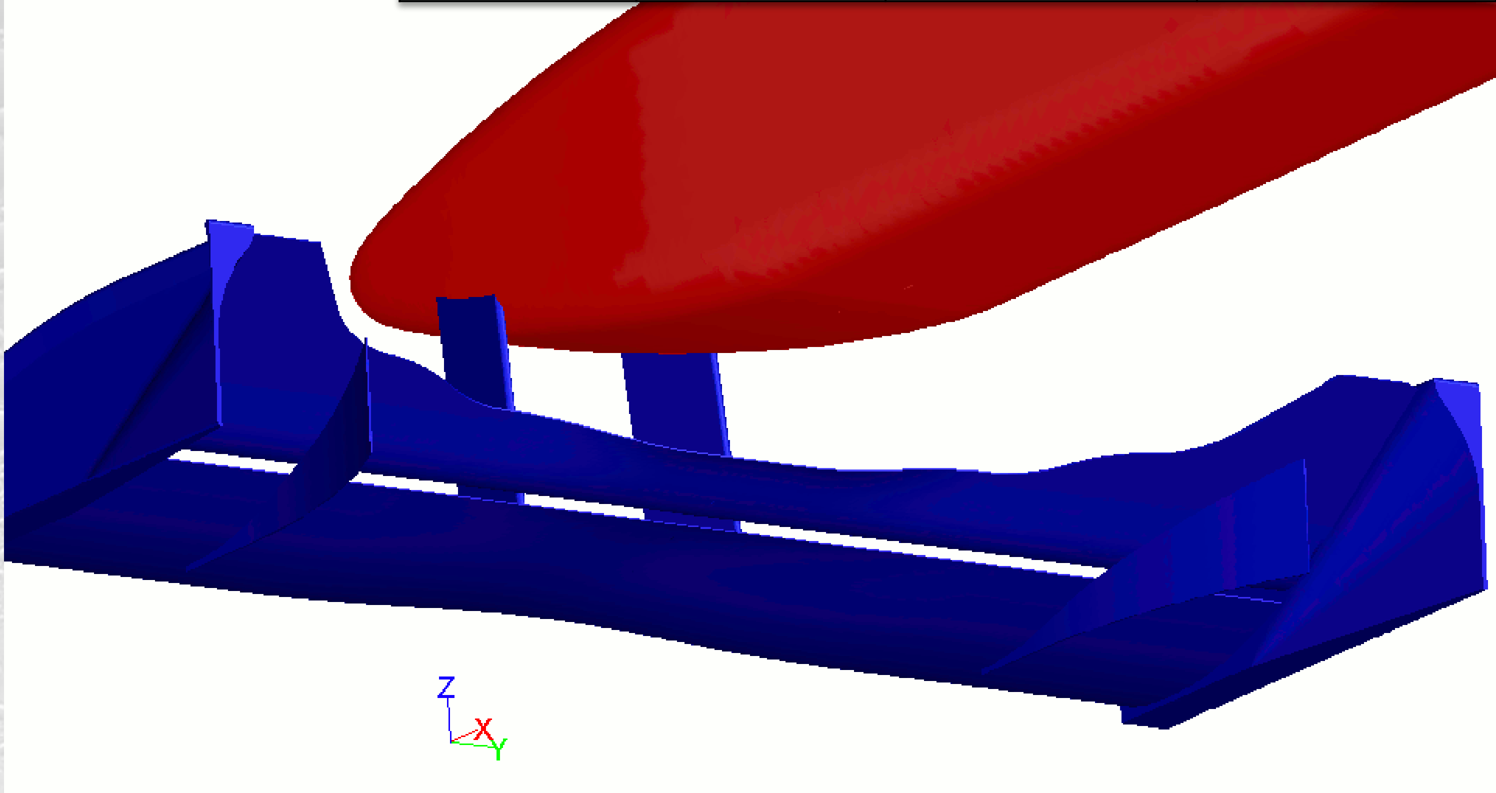
Morphing Preview (A=-1)

Apr 16, 2012
ANSYS FLUENT 14.0 (3d, pbns, rke)

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

Aeroelastic Analysis of Formula 1 Front Wing

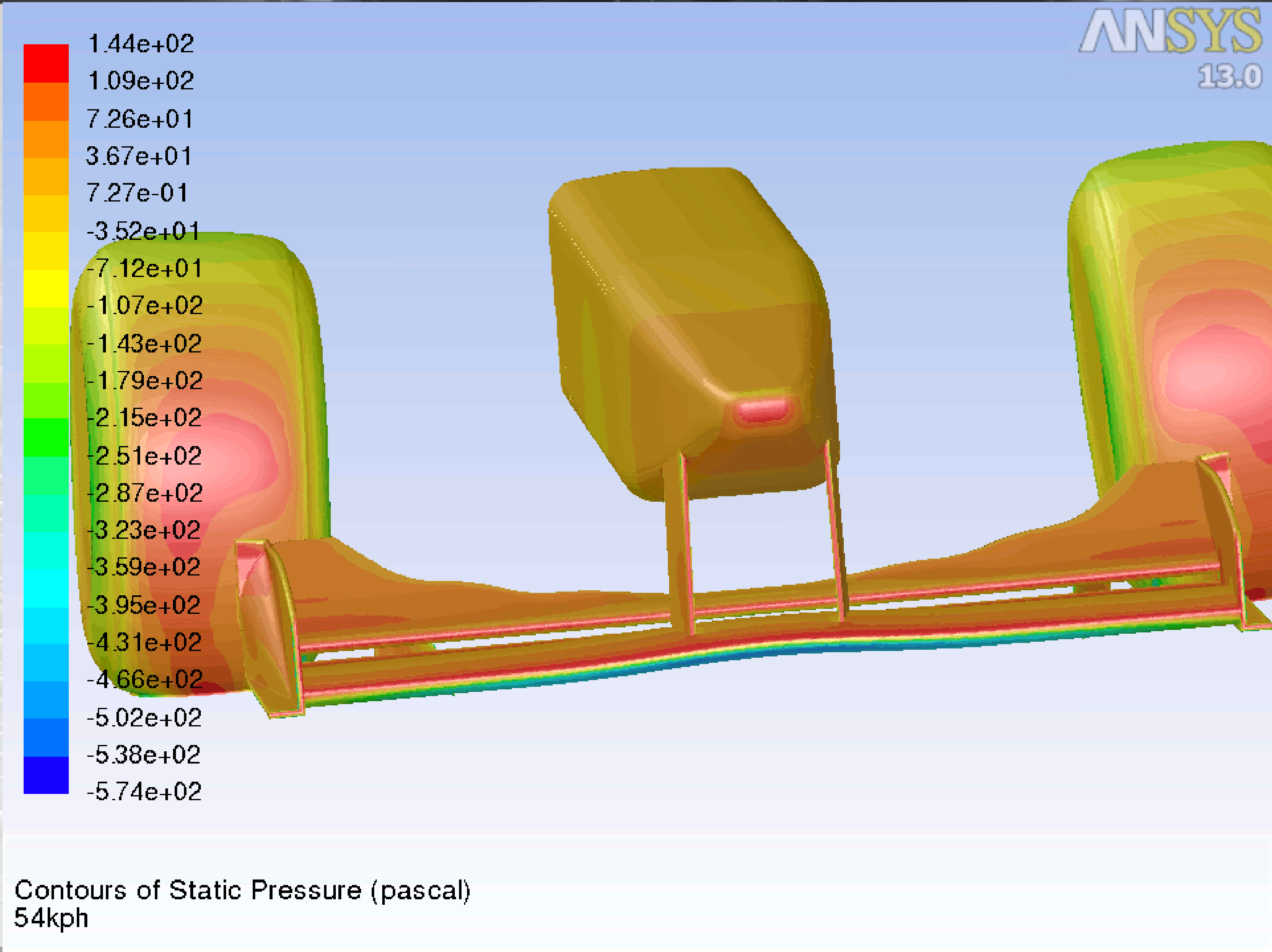
Mode	Disp(mm)	Max err(mm)	Max err (%)
1	7,19	1,61	22,39
2	7,19	0,86	12,00
3	6,98	0,85	12,15
4	6,90	0,66	9,50
5	6,85	0,19	2,76
2 Ways FSI	6,98	0,00	0,00



Morphing Preview (A=0)

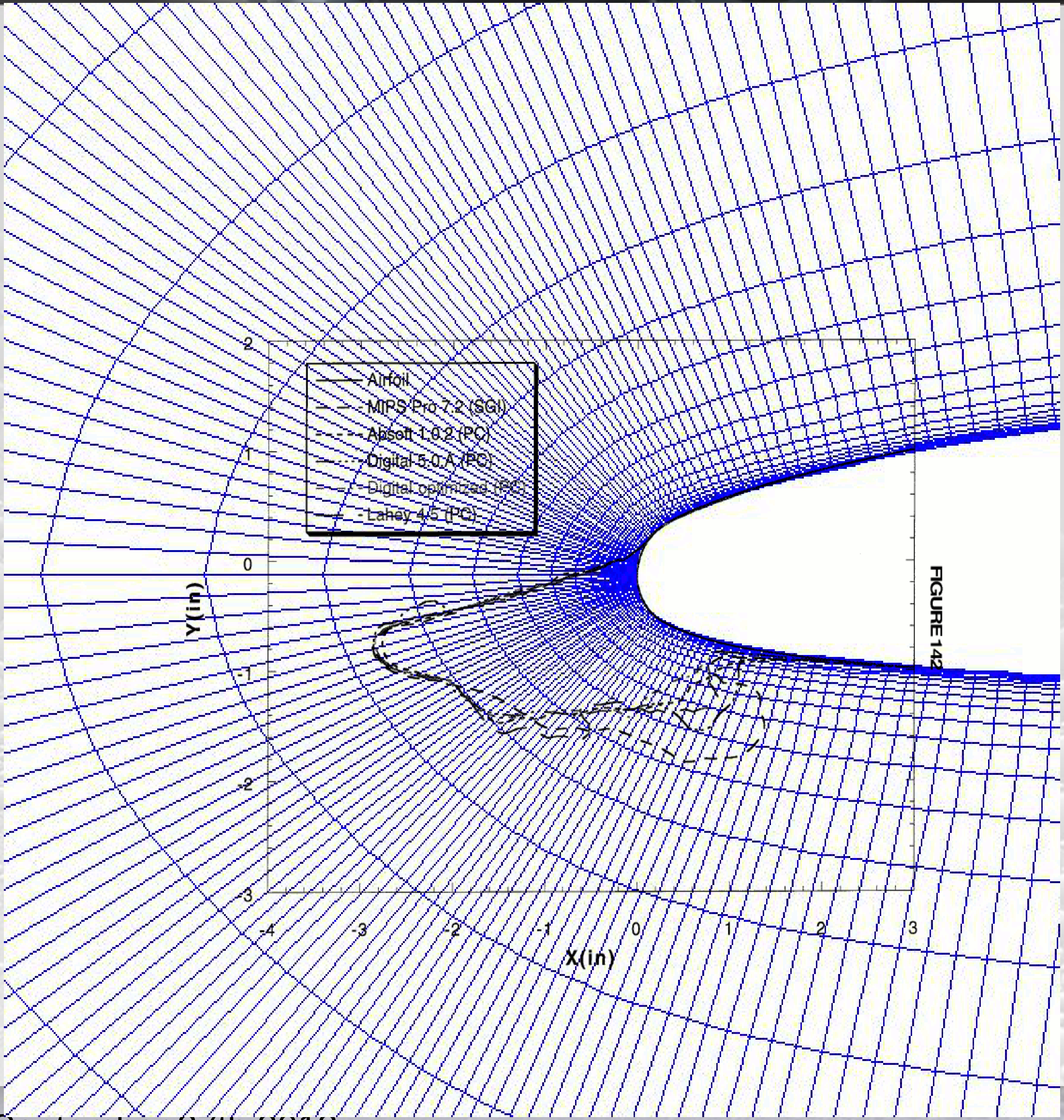
May 31, 2011
ANSYS FLUENT 12.1 (3d, pbns, rke)

Aeroelastic Analysis of Formula 1 Front Wing

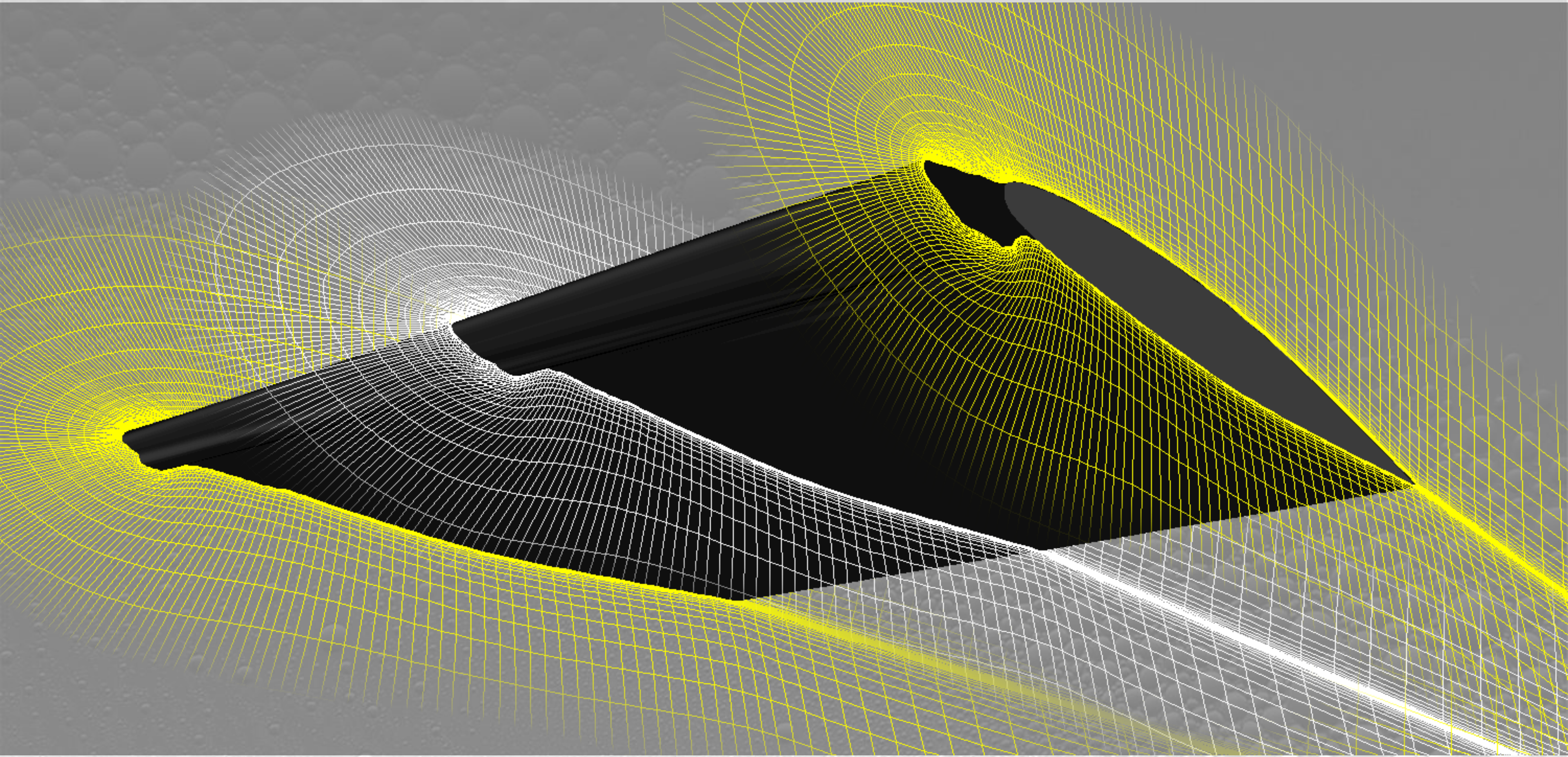


Contours of Static Pressure (pascal)
54kph

Ice accretion morphing



3D accretion morphing



MORPH lab

LET'S PLAY TOGETHER!

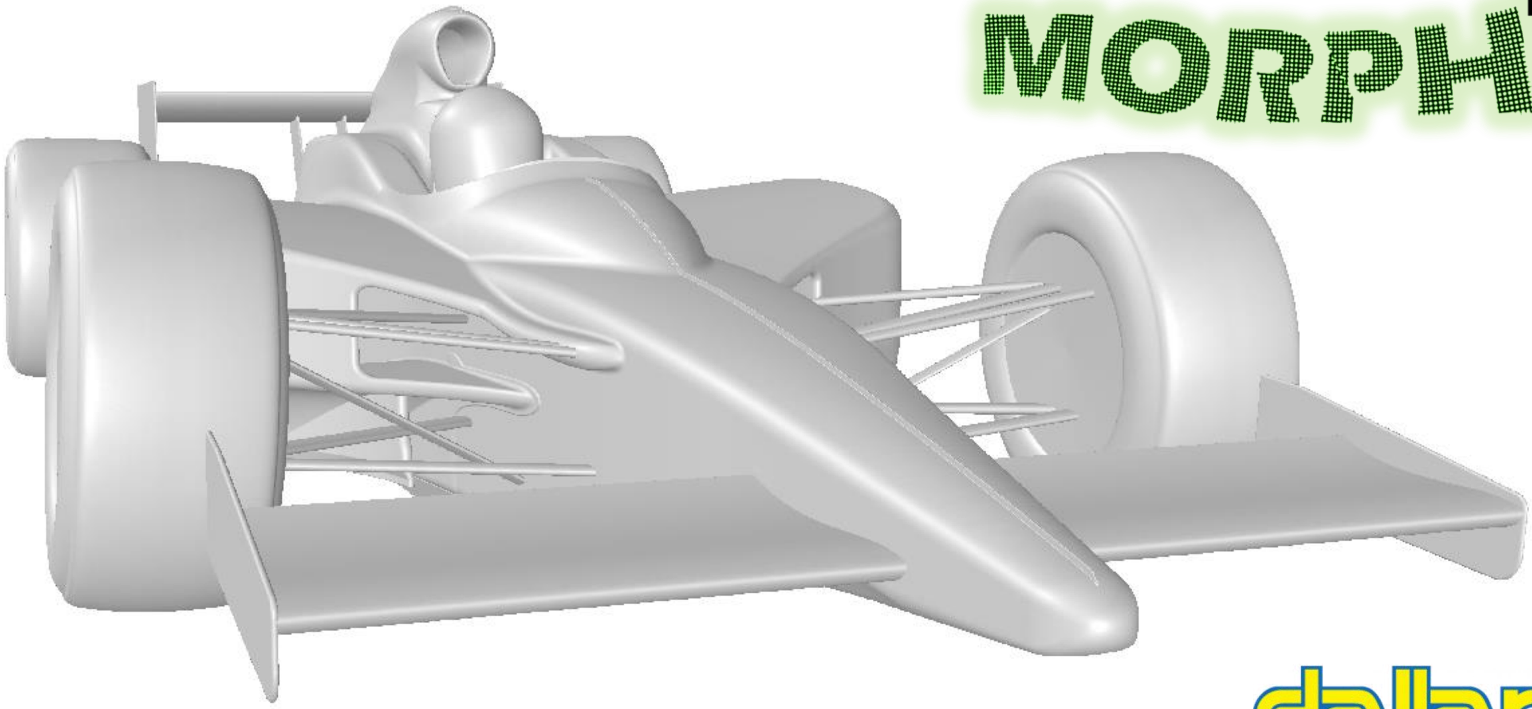
Tor Vergata

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.

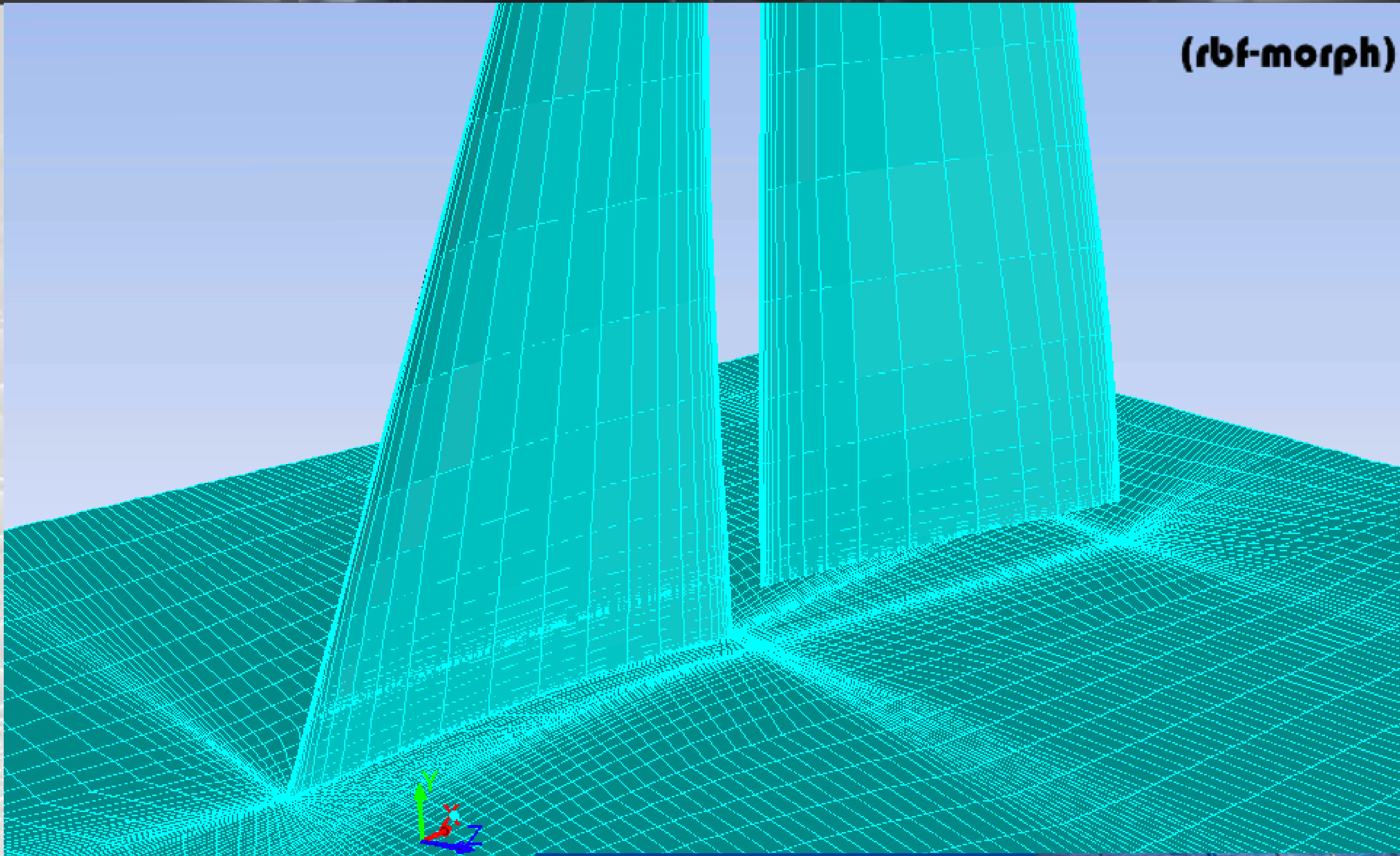
Why MorphLab?

- **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.



PRACE School, Ljubljana September 27th 2013

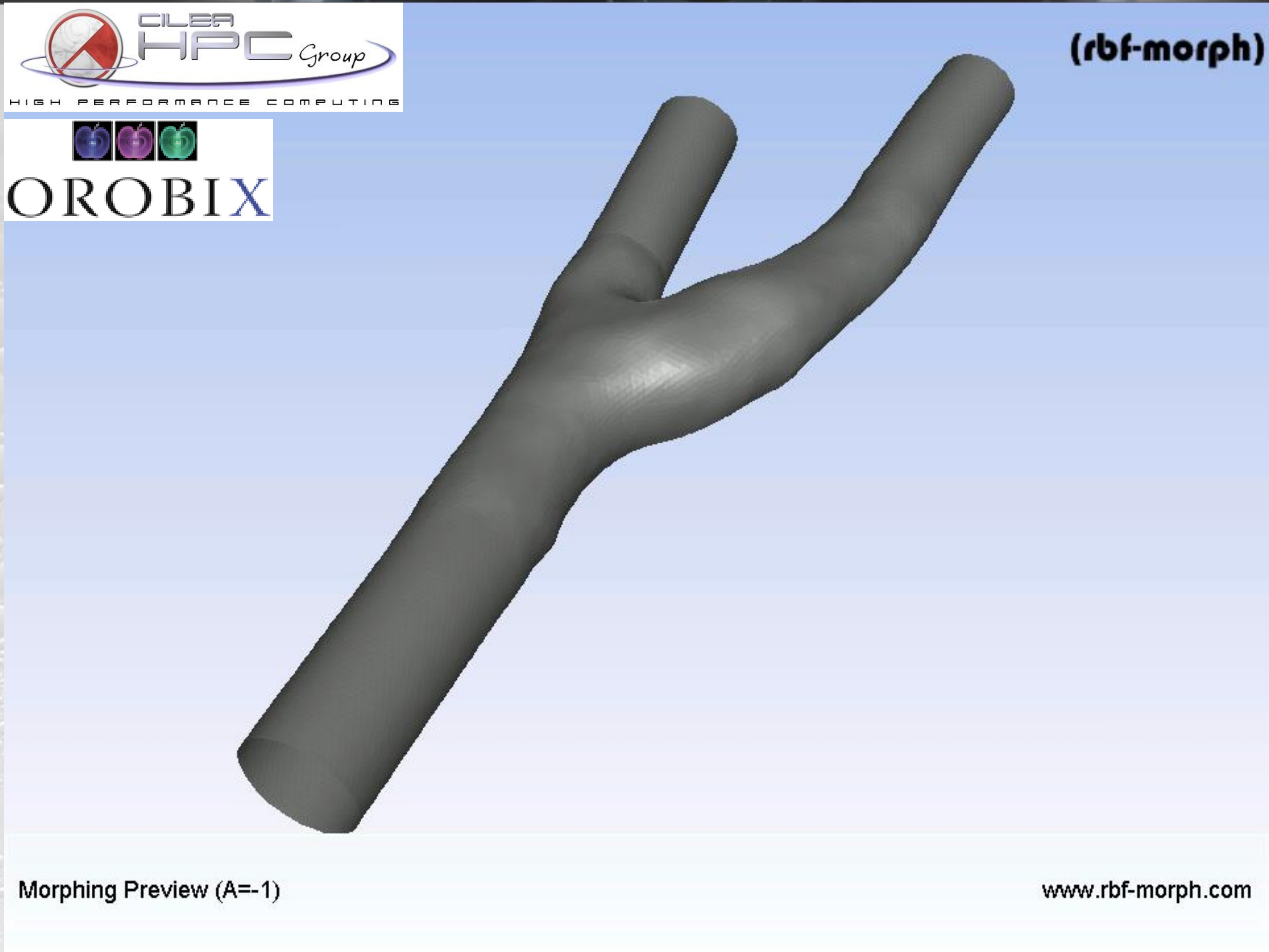
Sails Trim (Ignazio Maria Viola, University of Newcastle)



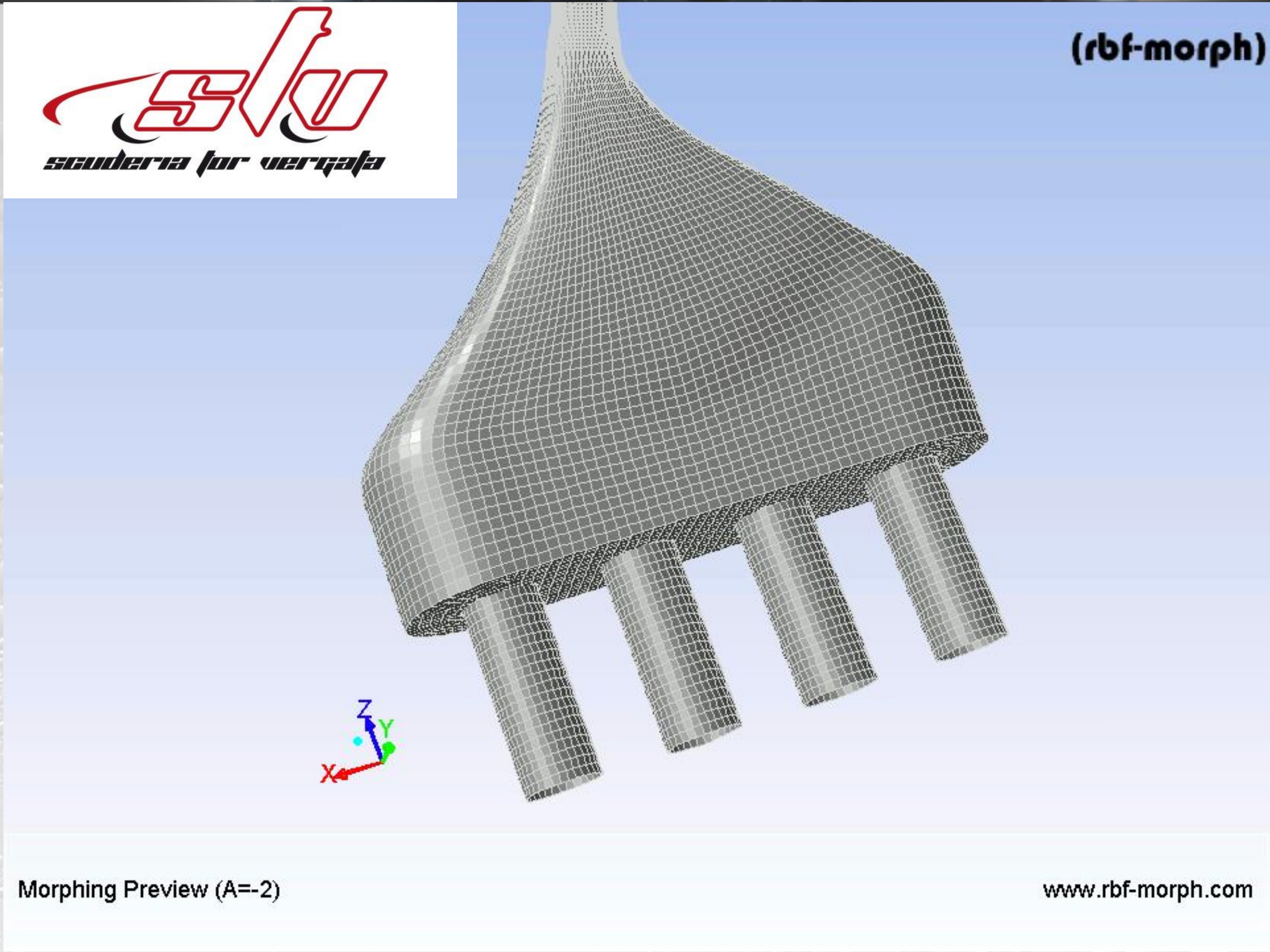
Morphing Preview (A=0)

ignazio.viola@ncl.ac.uk

Carotid Bifurcation (Orobix – CILEA)



Engine Air box shape
(STV FSAE Team)



Morphing Preview (A=-2)

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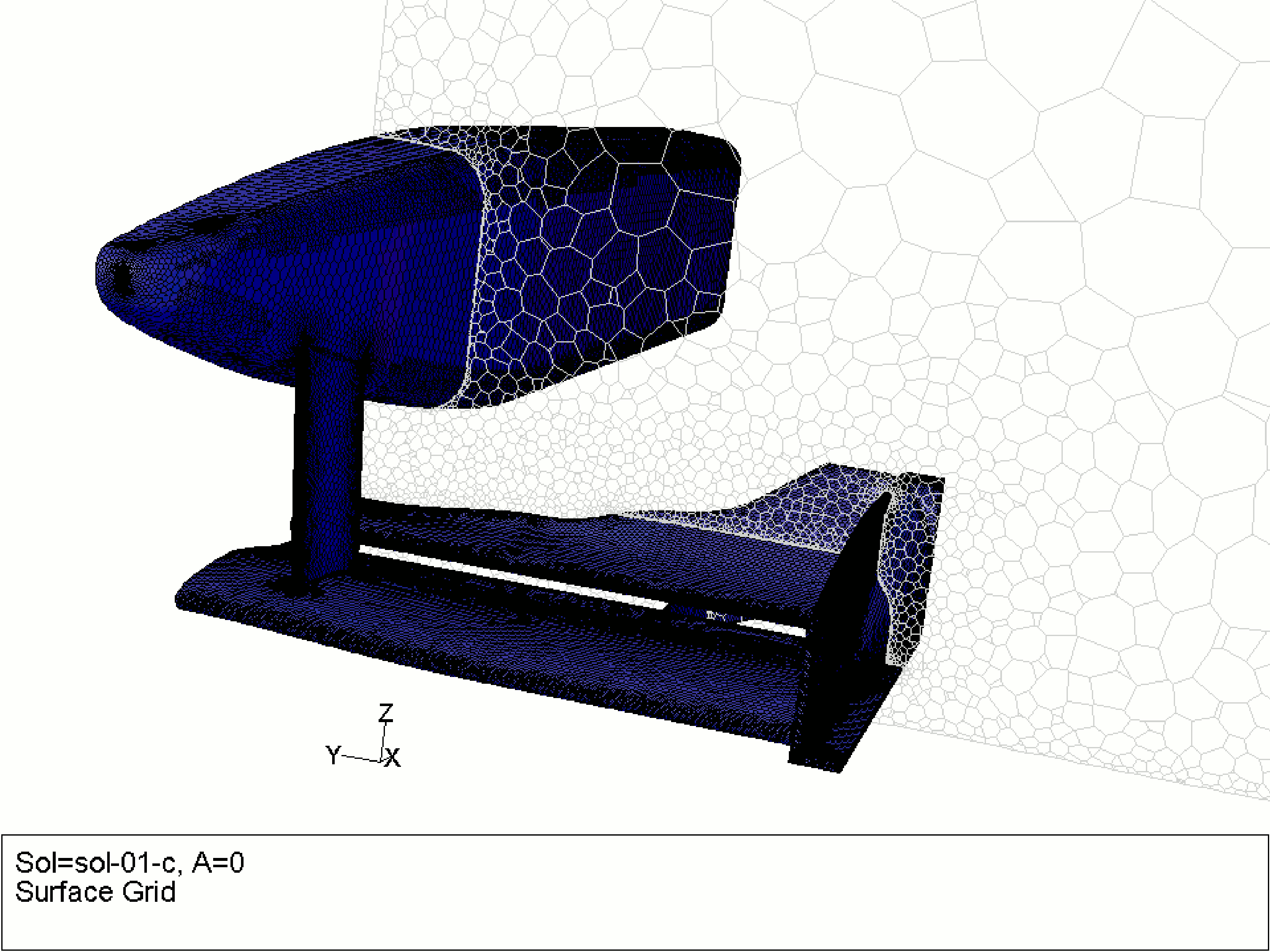
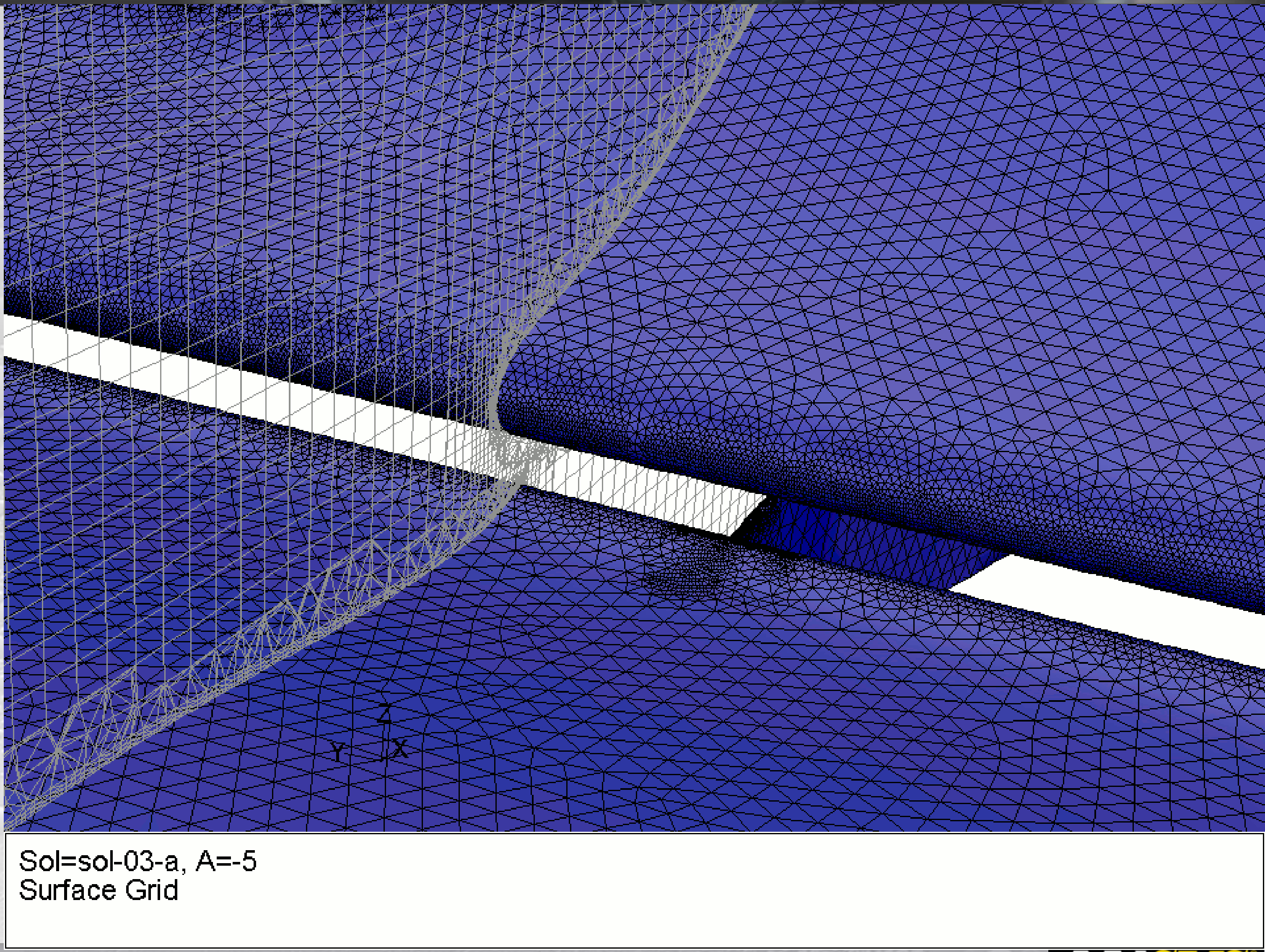
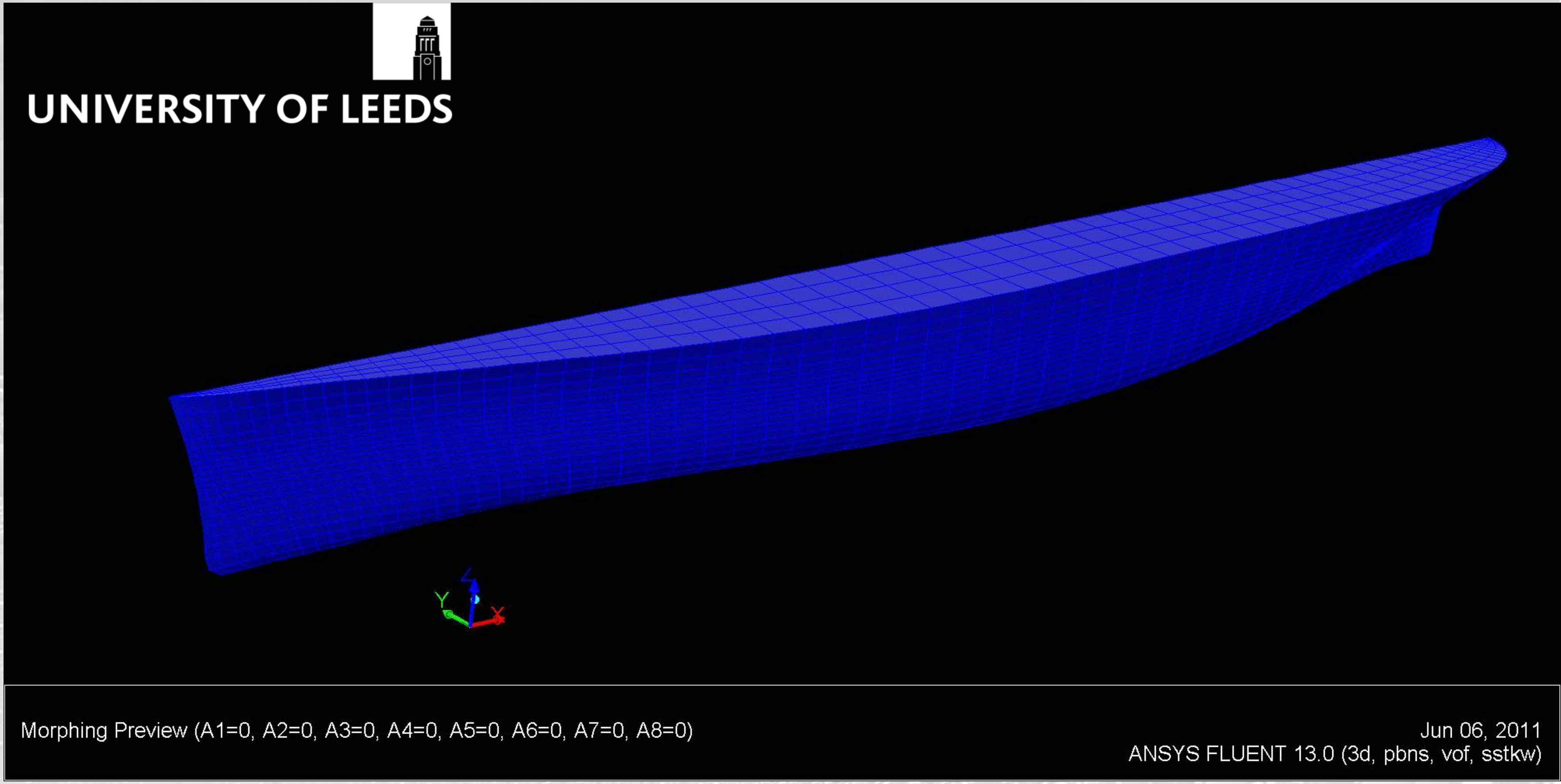
Generic Formula 1 Front End



Generic Formula 1 Front End



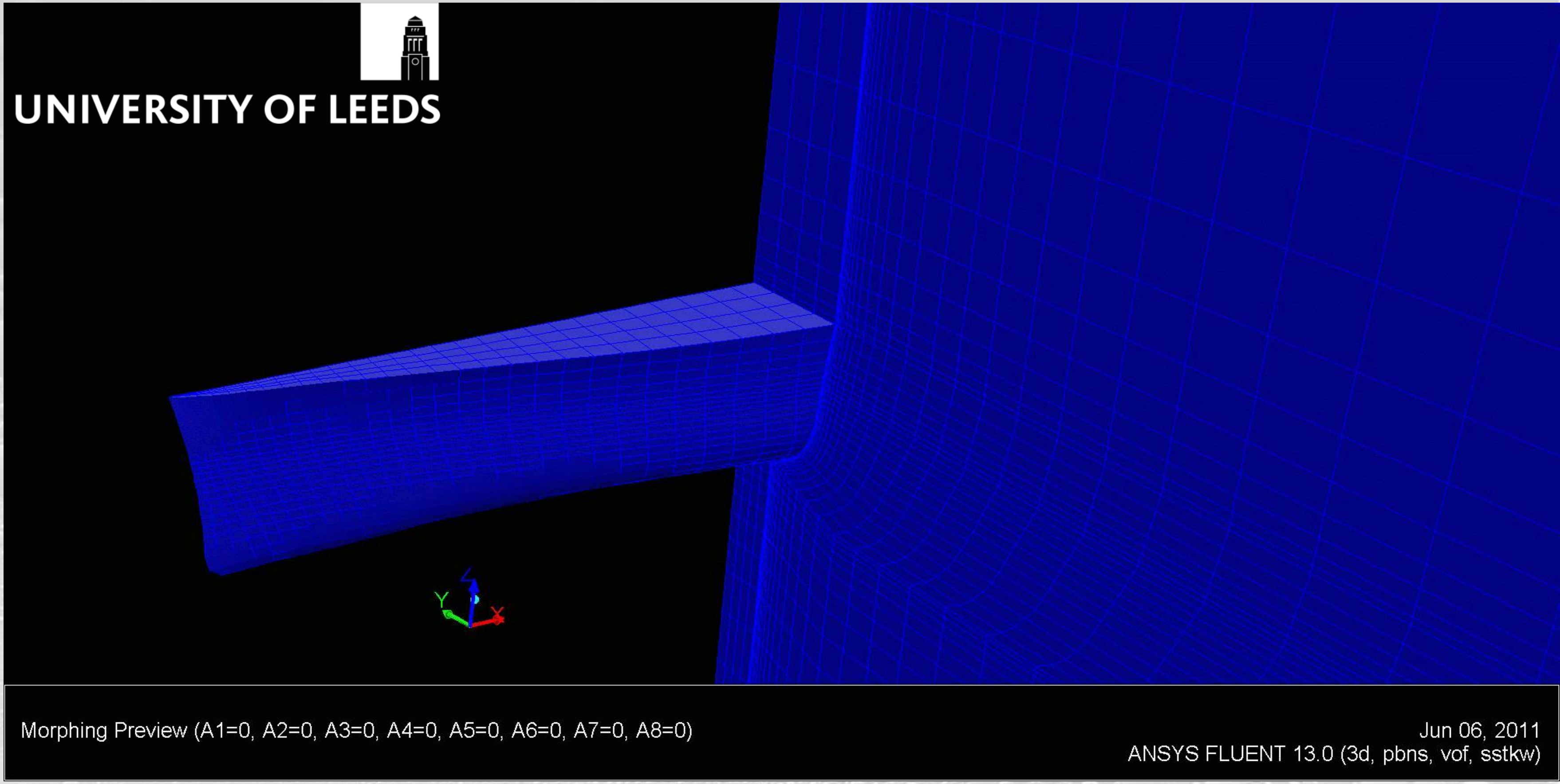
Ship Hull (University of Leeds)



Morphing Preview (A1=0, A2=0, A3=0, A4=0, A5=0, A6=0, A7=0, A8=0)

Jun 06, 2011
ANSYS FLUENT 13.0 (3d, pbns, vof, sstkw)

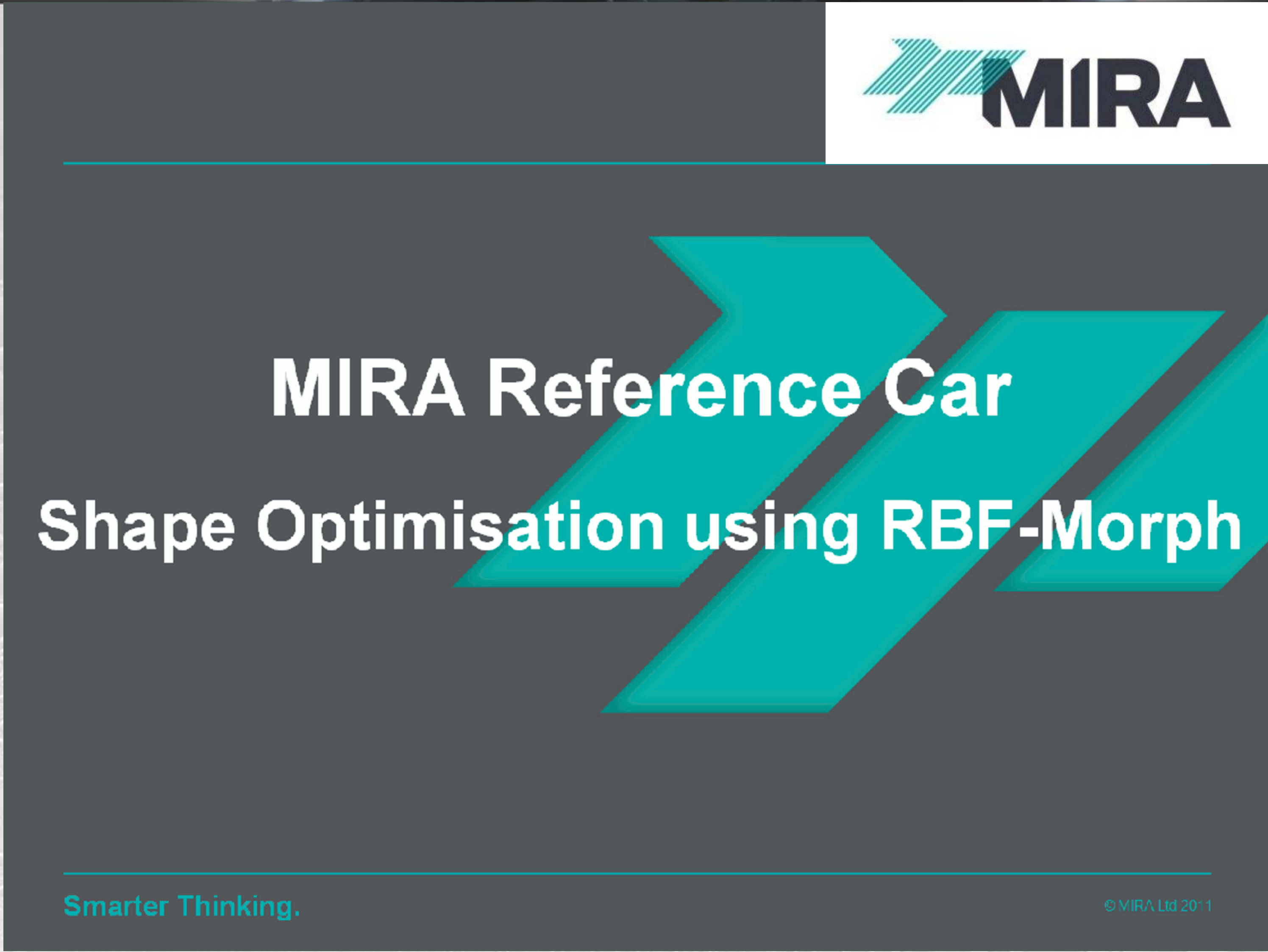
Ship Hull (University of Leeds)



Morphing Preview (A1=0, A2=0, A3=0, A4=0, A5=0, A6=0, A7=0, A8=0)

Jun 06, 2011
ANSYS FLUENT 13.0 (3d, pbns, vof, sstkw)

MIRA Reference car
(MIRA ltd)



MIRA

MIRA Reference Car

Shape Optimisation using RBF-Morph

Smarter Thinking.

© MIRA Ltd 2011

Modeling Guidelines

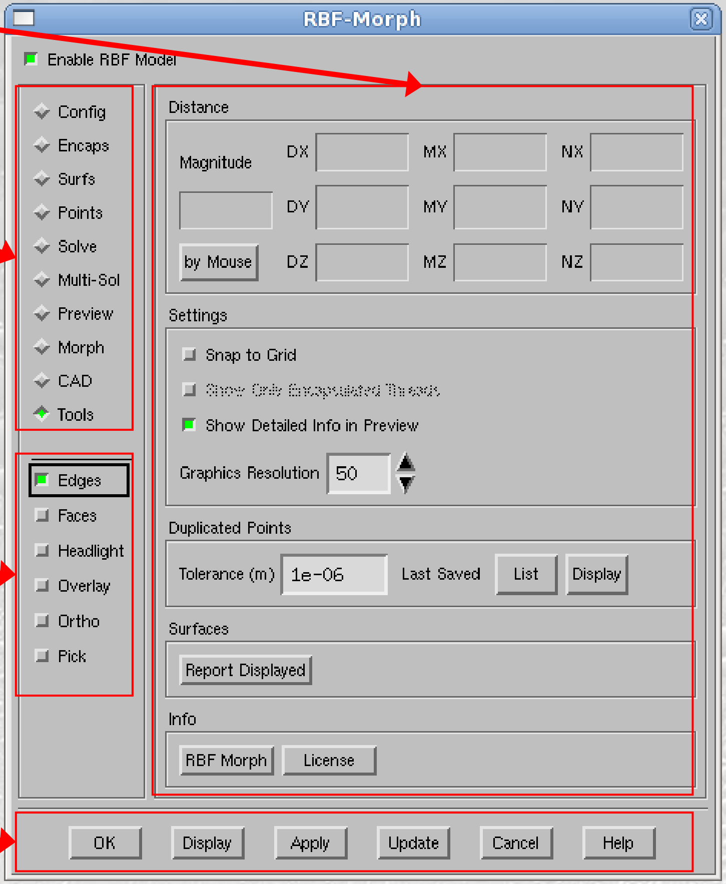
RBF Morph GUI overview

Switchable Panel

Main Sidebar

Graphics Sidebar

Common Buttons



☑ Enable RBF Model

☐ Snap to Grid

☐ Show Only Encapsulated Threads

☑ Show Detailed Info in Preview

Graphics Resolution 50

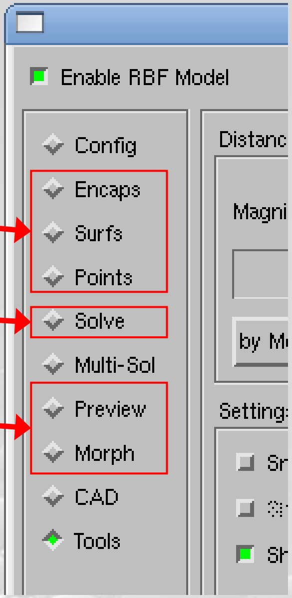
Tolerance (m) 1e-06

☑ Edges

- Several operative modes are accessed changing the **Switchable Panel** acting on the **Main Sidebar**
- The normal setup process of the *RBF Morph* usually requires to use the panels from top to bottom.
- The graphics settings of the **Graphics Sidebar** are available at any time.

Setup of a single shape modifier

- **Step 1 setup** and definition of the problem (source points and displacements).
- **Step 2 fitting** of the RBF system.
- **Step 3 morphing** of the surface and volume mesh.
- Steps are iterated until a good result is achieved, the shape modifier is then stored.
- The user can define several shape modifiers in the same fashion; they can be combined during the solution stage (serial/parallel – interactive/batch)



Encapsulations

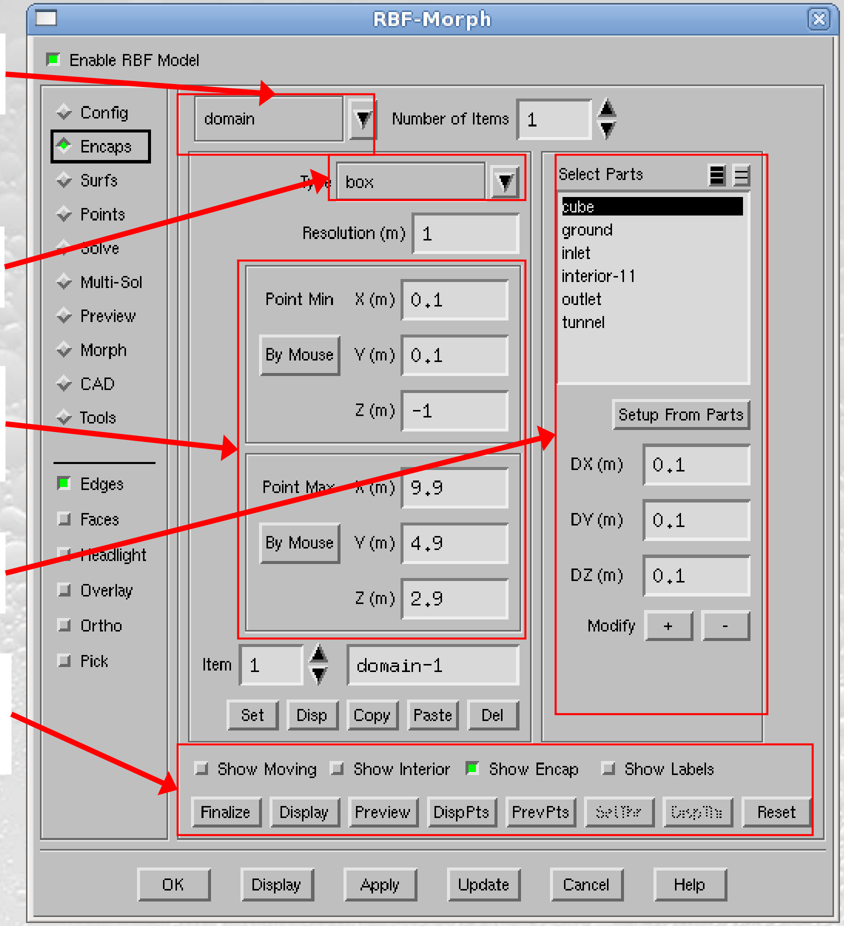
Encap kind

Encap Shape

Active Encap Parameters

Setup from Parts

Multi Encap Management



☑ Enable RBF Model

domain ▼ Number of Items 1

Type box ▼

Resolution (m) 1

Point Min X (m) 0.1 Y (m) 0.1 Z (m) -1

Point Max X (m) 9.9 Y (m) 4.9 Z (m) 2.9

Item 1 domain-1

Select Parts: cube, ground, inlet, interior-11, outlet, tunnel

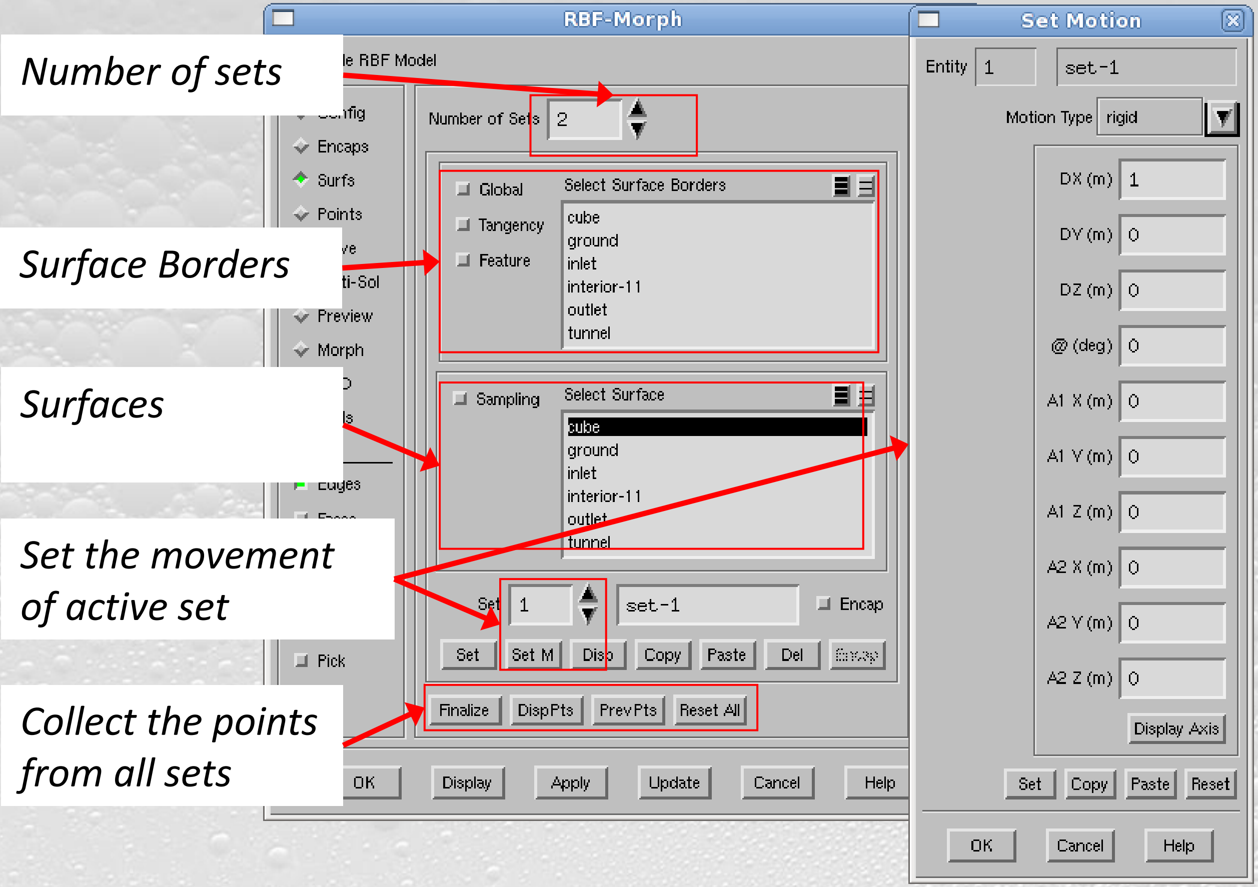
DX (m) 0.1
DY (m) 0.1
DZ (m) 0.1

☑ Edges
☐ Faces
☐ Headlight
☐ Overlay
☐ Ortho
☐ Pick

☐ Show Moving ☐ Show Interior ☑ Show Encap ☐ Show Labels

- The Encapsulation technique is used to define sub-domains of the model on which the morpher action is applied, using various basic shapes.
- Source Points are located on Encap borders with a prescribed resolution

Surfaces



Number of sets

Surface Borders

Surfaces

Set the movement of active set

Collect the points from all sets

Number of Sets 2

Entity 1 set-1

Motion Type rigid

DX (m) 1

DY (m) 0

DZ (m) 0

@ (deg) 0

A1 X (m) 0

A1 Y (m) 0

A1 Z (m) 0

A2 X (m) 0

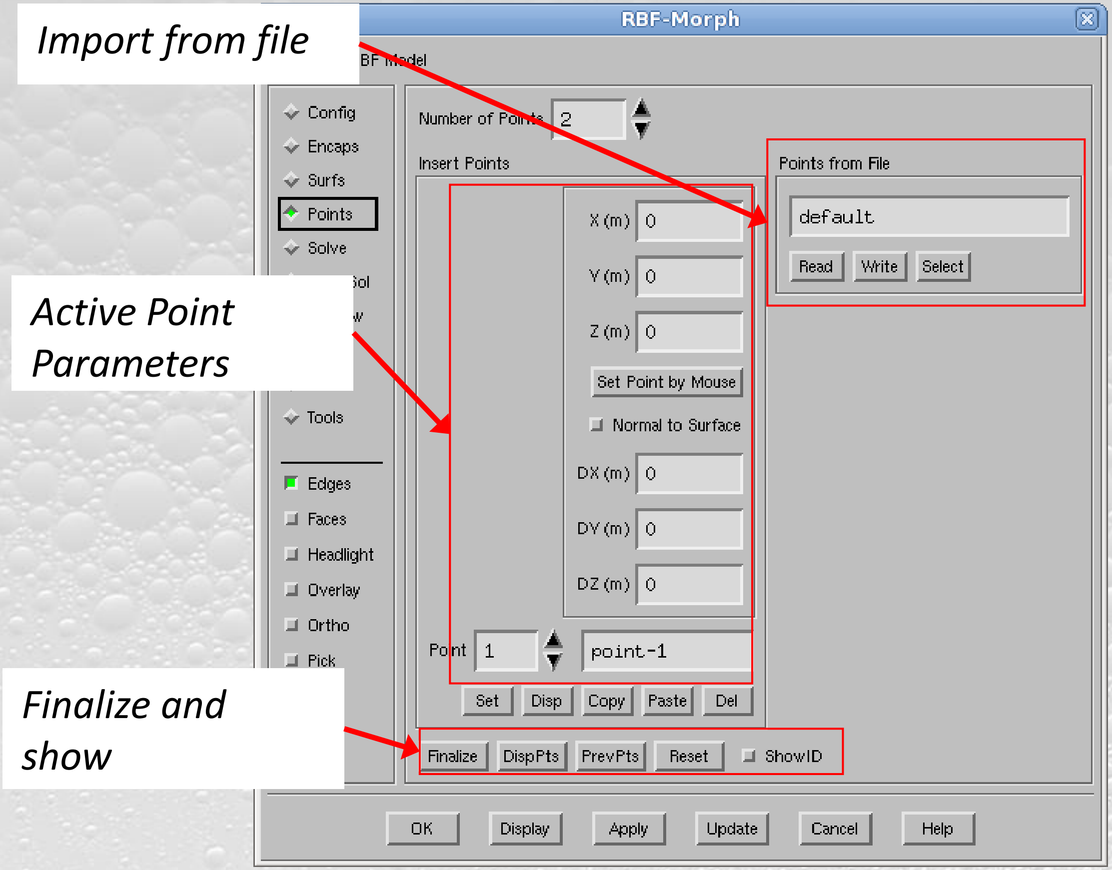
A2 Y (m) 0

A2 Z (m) 0

Set 1 set-1

- Source points are extracted from mesh surfaces in various ways (border, feature edges or entire mesh thread).
- A generic number of surface sets can be selected, each of them containing groups of surfaces.
- A specific independent motion can be assigned for each set.

Points



Import from file

Active Point Parameters

Finalize and show

Number of Points: 2

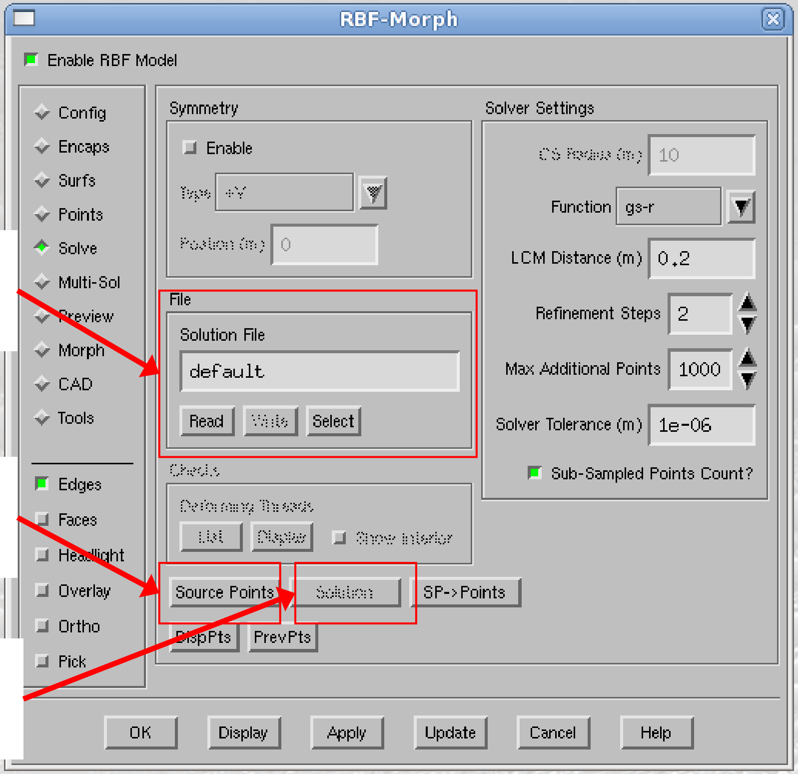
Points from File: default

X (m): 0
Y (m): 0
Z (m): 0
DX (m): 0
DY (m): 0
DZ (m): 0

Point: 1 point-1

- In this panel it is possible to specify individual source points by coordinates and a specific independent motion can be assigned for each point.
- Points from file
- Points from a standard *RBF Morph* Set up

Solve



☑ Enable RBF Model

☑ Edges
☐ Faces
☐ Headlight
☐ Overlay
☐ Ortho
☐ Pick

☐ Enable
Type +Y
Position (m) 0

Solution File default

CS Radius (m) 10
Function gs-r
LCM Distance (m) 0.2
Refinement Steps 2
Max Additional Points 1000
Solver Tolerance (m) 1e-06
☑ Sub-Sampled Points Count?

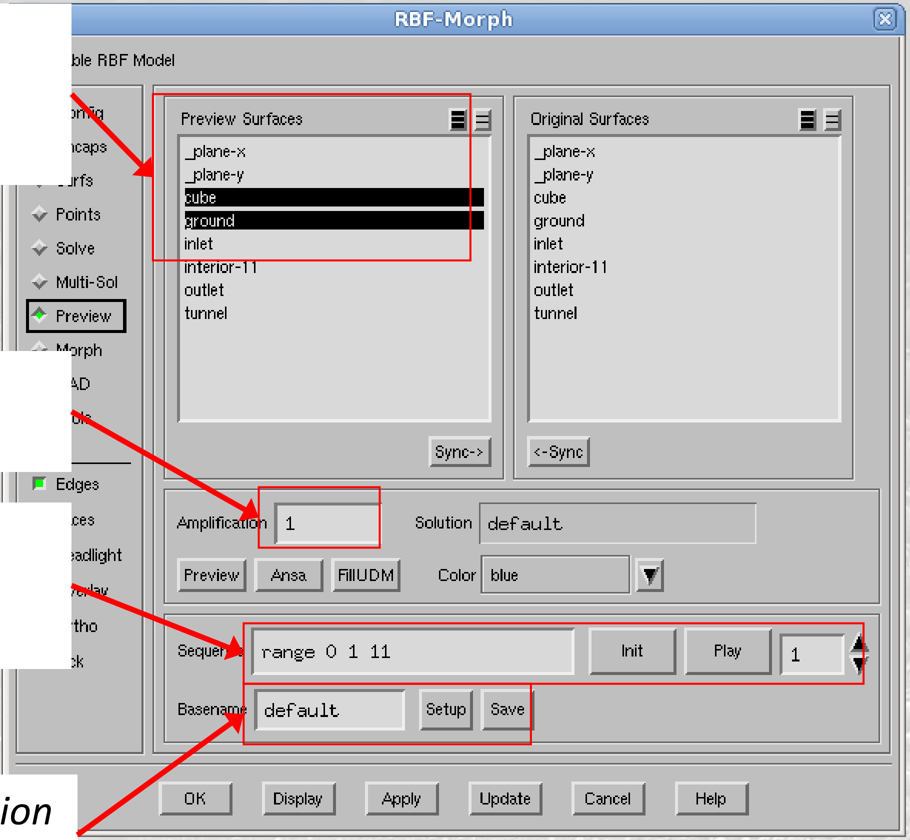
Load/Save a solution file

Collect all the Source Points

Solve the RBF Problem

- After the selection of the source points is completed through at least one of the steps *Encaps*, *Surfs* and *Points*, the RBF solution can be generated in this panel.

Preview



Surfaces to be previewed

Desired amplification

Amplification range for animation

Export animation frames

Preview Surfaces: _plane-x, _plane-y, cube, ground, inlet, interior-11, outlet, tunnel (selected: cube, ground)

Original Surfaces: _plane-x, _plane-y, cube, ground, inlet, interior-11, outlet, tunnel

Amplification: 1

Solution: default

Color: blue

Sequence: range 0 1 11

Basename: default

- The effect of shape modifier can be verified directly on the **surface mesh**
- Surface elements quality is reported
- The **amplification** can be fixed or a **sequence** to be used for an animation

Morph

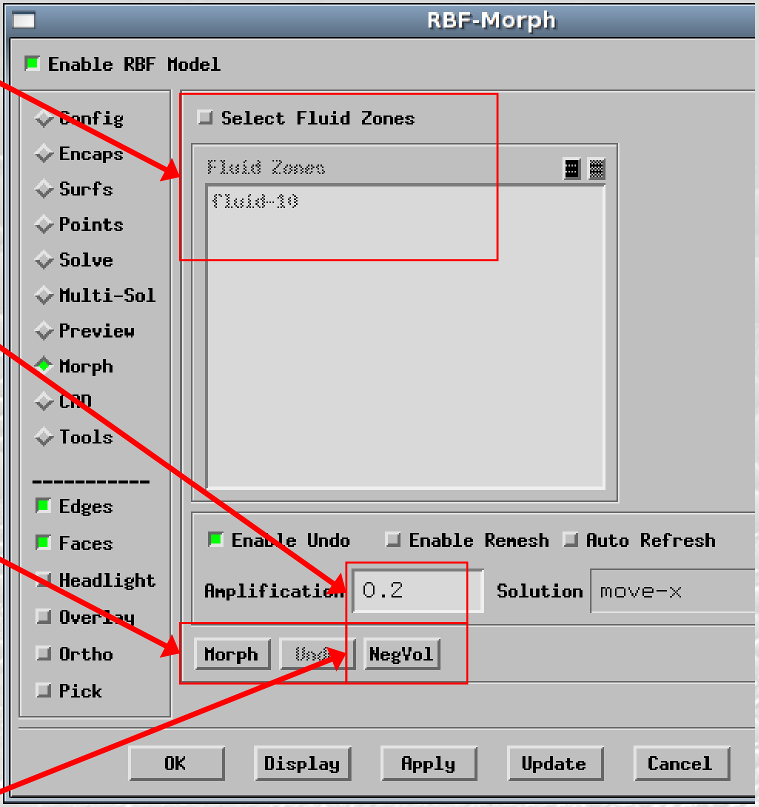
Fluid Zones affected by the morpher

Desired amplification

Morph the Volume Mesh

Restore the original mesh

Show Negative Volumes



Amplification 0.2

Solution move-x

- The effect of shape modifier can be verified directly on the **fluid mesh**
- Range of amplification (i.e. valid mesh, mesh quality) using the **Undo** feature
- Critical areas where **negative volumes** are generated can be highlighted in the graphic viewport

Modeling guidelines: basic options

- Use **Surfs** only: specify the motion field for each Surface Set (RBF Points are extracted from surfaces or borders). A portion of a surface can be extracted using a **Selection** Encap (one for each set). Default motion is a **zero movement** for surfaces that need to be constrained. All surfaces without a prescribed motion will be deformed by the morpher.
- Use **Encaps** only: specify the motion of each **Moving Encap** (RBF Points are generated on Encap Surfaces using desired resolution). The morpher action can be limited using **Domain Encaps**.

Modeling guidelines: basic options

- Use **Points** only: specify directly position and displacements of all RBF Points. Points can be defined **everywhere**; a snap to surface option is available, in this case the movement can be prescribed with respect to local surface **normal** vector.
- Direct **Points** definition gives the full access to RBF technology. Special set-up can be defined importing points from **file** or defining points with **scheme** scripts.
- Combining the **three criteria** makes the morpher **flexible** for a wide range of applications.

Modeling guidelines: advanced options

- For **large** meshes set-up can be improved to reduce the **number** of **RBF Points** (saving both fit and morphing CPU time).
- **Combine Surfs and Encaps**: domain Encaps can be defined to limit the morpher action. Moving Encap can be defined to protect parts inside the morphing domain. No mesh nodes will be extracted in parts of Surfaces that fall outside the domain Encaps or inside the Moving Encaps.
- **Two steps** approach: a first RBF problem is defined to fine control the deformation of a surface set. Obtained solution is then reused as input for such surface set in a second RBF problem optimized for mesh volume morphing.

Modeling guidelines: advanced options

- **Advanced surface control** (usually used in two steps approach): use **Points** only in the first stage. Use Surfs and Encap in the second Step.
  - Surfaces can be finely controlled using points located onto the surfaces.
  - The **SP2Points** feature allows to control surfaces using special geometry (deforming box as FFD).
- Surface can be controlled using an **STL surface** as a target.
- Surface can be controlled using a **FEM** solution, even if available on a different non conformal mesh (beams models allows to update surfaces).

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/).

Thank you for your attention!

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