RBF Morph: a fast meshless morpher for Fluent

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ABSTRACT

The present paper gives an overview of a new add-on module available for Ansys FLUENT: RBF Morph. A comprehensive description of the working principles has been already presented at ANSYS EASC 2009 [1] through an industrial application: the optimisation of a motorbike windshield. The same study is herein summarized together with a new one: the morphing of a Formula 1 front wing. The aim of the paper is to outline the performance of RBF Morph for industrial problems in terms of speed, problem complexity, model size and final mesh quality.

1. INTRODUCTION

Fluid dynamic development is a very crucial task, especially for problems where the motion of a fluid has an important impact on performances. In fact, a slight shape modification can dramatically affect the behaviour of a component that interacts with the fluid. CFD can give an important aid to drive the design of such critical components but a lot of effort is required if several configurations have to be considered. This is because an efficient parametric CFD solver, suitable for optimization, is still missing on the market, especially when large problems need to be handled.

Shape parameterization is available in the CAD model, used as starting point for CFD model generation; however the steps required to generate the mesh are very complex and parametric properties and geometric features of the original CAD model are usually lost.

For this reason an effective approach consists in studying the effects of slight modifications acting directly on the CFD mesh. Required modifications can be introduced by morphing the surface mesh at the boundary of fluid mesh and propagating such deformations inside the domain by means of a smoother. Original mesh topology is preserved but the final quality of the mesh depends on the action of the surface morpher and the fluid smoother.

In this paper the new morphing product RBF Morph is presented, starting from the description of the background theory of Radial Basis Functions used for the implementation of the numerical kernel of the software.

To better understand how RBF Morph can be used for industrial cases, some examples are presented.

2. RBF MORPH

The new product RBF Morph, an integrated system for morphing and shape optimization tailored for the CFD solver ANSYS Fluent, is herein presented. RBF Morph is fully integrated in the CFD solving process and combines a very accurate control of the geometrical parameters with an extremely fast mesh deformation. RBF Morph is the result of the joint between academic state-of-the-art research and top-level industrial needs. In the present implementation, the morpher has been tailored to ANSYS Fluent. However, the kernel of the software represents the most sophisticated component and could be adapted to different tasks or stand-alone work.

2.1 The aim

The aim of the RBF Morph is to perform fast mesh morphing using a mesh-independent approach based on state-of-the-art RBF (Radial Basis Functions) techniques.

The use of RBF Morph allows the CFD user to perform shape modifications, compatible with the mesh topology, directly in the solving stage, just adding one single command line in the input file.
The most important requirements are:

- mesh-independent solution;
- parallel morphing of the grid;
- large size models (many millions of cells) must be morphed in a reasonable short time
- management of every kind of mesh element type (tetrahedral, hexahedral, polyhedral, prismatic, hexcore, non-conformal interfaces, etc.).

The final goal is to perform parametric studies of component shapes and positions typical of the fluid-dynamic design like:

- design Developments;
- multi-configuration studies;
- sensitivity Studies;
- DOE (Design Of Experiment);
- optimization.

2.2 Background

A system of radial functions is used to produce a solution for mesh movement/morphing, from a list of source points and their displacements [2,3]. This approach is valid for both surface shape changes and volume mesh smoothing.
Radial basis were born as an interpolation tool for scattered data and consist of a very powerful tool because they are able to interpolate everywhere in the space a function defined at discrete points giving the exact value at original points. The behaviour of the function between points depends on the kind of basis adopted.
The radial function can be fully or compactly supported, in any case a polynomial corrector is added to guarantee compatibility for rigid modes.
Typical radial functions are reported in the following table.

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)	$\dfrac{1}{\sqrt{1+r^2}}$
Inverse quadratic (IQ)	$\dfrac{1}{1+r^2}$
Gaussian (GS)	e^{-r^2}

As will be shown in detail, a linear system (of order equal to the number of source point introduced) need to be solved for coefficients calculation. Once the unknown coefficients are calculated, the motion of an arbitrary point inside or outside the domain (interpolation/extrapolation) is expressed as the summation of the radial contribution of each source point (if the point falls inside the influence domain).
Details of the theory need to be given using some equations. An interpolation function composed by a radial basis and a polynomial is defined as follows:

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

The degree of the polynomial has to be chosen depending on the kind of radial function adopted. A radial basis fit exists if the coefficients γ and the weight of the polynomial can be found such that the desired function values are obtained at source points and the polynomial terms gives 0 contributions at source points, that is:

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

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

The minimal degree of polynomial p depends on the choice of the basis function. A unique interpolant exists if the basis function is a conditionally positive definite function. If the basis functions are conditionally positive definite of order m <= 2, a linear polynomial can be used. The subsequent exposition will assume valid the aforementioned hypothesis. A consequence of using a linear polynomial is that rigid body translations are exactly recovered. The values for the coefficients γ and the coefficients β of the linear polynomial can be obtained by solving the system:

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

where g are the know values at the source points. M is the interpolation matrix defined calculating all the radial interactions between source points:

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

and P is a constraint matrix that arises balancing the polynomial contribution and contains a column of “1” and the x y z positions of source points in the others three columns:

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

Radial basis interpolation works for scalar fields. For the smoothing problem each component of the displacement field prescribed at the source points is interpolated as follows:

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

Radial basis method has several advantages that make it very attractive in the area of mesh smoothing. The key point is that being a meshless method only grid points are moved regardless of element connected and is suitable for parallel implementation. In fact, once the solution is known and shared in the memory of each calculation node of the cluster, each partition has the ability to smooth its nodes without taking care of what happens outside because the smoother is a global point function and the continuity at interfaces is implicitly guaranteed.

2.3 How does it work

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.

RBF Morph requires three different steps:

- Step1: [SERIAL] setup and definition of the problem;

- Step2: [SERIAL] solution of the RBF system;
- Step3: [SERIAL/PARALLEL] morphing of surface and volume mesh.

The serial setup requires an intense use of RBF Morph GUI. The GUI offers several tools for the definition of the problem. It is composed by a switchable principal panel (Figure 1). Acting on the radio buttons on the left 8 different operative modes are accessed. The first 4 panels (Config, Encaps, Surfs, Points) are addressed to problem set-up, the other 3 (Solve, Preview, Morph) allows to calculate the rbf solution, to preview its effect and to apply it for morphing and the last panel contains some utilities useful for the RBF Morph software.

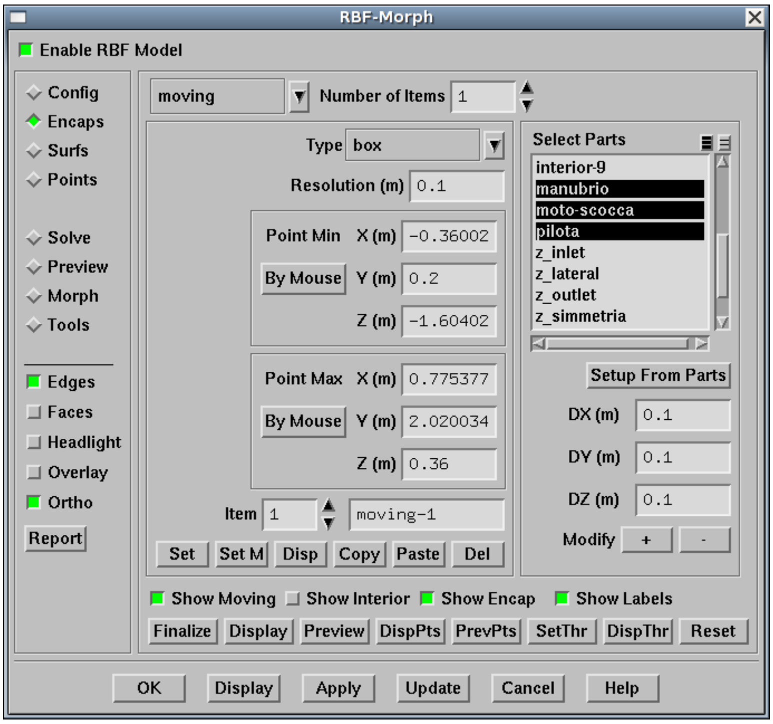

Figure 1: GUI of RBF Morph. The “Encaps” panel is shown

After completing the step1 it is possible to pass to the step2 and calculate the rbf solution. The effect of an imposed modifier can be verified previewing its action (an arbitrary number of surfaces can be morphed on the fly showing the results in the Fluent graphic viewport) without moving the nodes, or exploiting the undo capability that allows to examine the morphed mesh checking its quality and the possible appearing of negative cell volume areas. Once that the modifier is acceptable it can be saved on file. The operation can be repeated for each desired modifier.

The third step can be performed in serial or in parallel with or without the GUI. Once that the solutions are available they can be loaded and used to morph the mesh using the morph panel of the GUI or they can directly used by means of TUI commands that allow to prescribe a single morph or a multi-morph summing the effect of multiple modifiers. Considering that each modifier can be applied with the desired magnitude (i.e. a scalar to set the intensity of the modifier) a parametric Fluent model results.

Since the modifiers are non-linear and large mesh motion are involved the effect of multiple modifier action depends on the application command sequence. For this reason, the multi-morph command superimpose the effects using the same baseline mesh as the starting point of each modifier. Different sequences can be imposed by the user applying the single morph after the action of a previous morph. But in this case a wise procedure is to direct control the effect of the sequence of morphing. For special cases a custom sequence of morphing actions can be programmed as an additional UDF.

3. OPTIMISATION METHODOLOGY

Thanks to RBF Morph the Fluent model becomes parametric. Of course this is not a new feature. Several parameters are available for standard Fluent analysis and usually they can be controlled by means of journal files and scripts. The new feature is that shape parameters become available and can be controlled basically in two ways:

- by means of the interactive Multi-Sol panel the user can set-up desired modifiers and amplifications (Figure 2);
- by means of a TUI commands also available in batch and parallel mode.

For example, considering the same modifiers of the example reported in Figure 2, the RBF-Morph batch command line is:

(rbf-morph '(("rotate-driver" 0.45)("rotate-deflector" -0.2)))

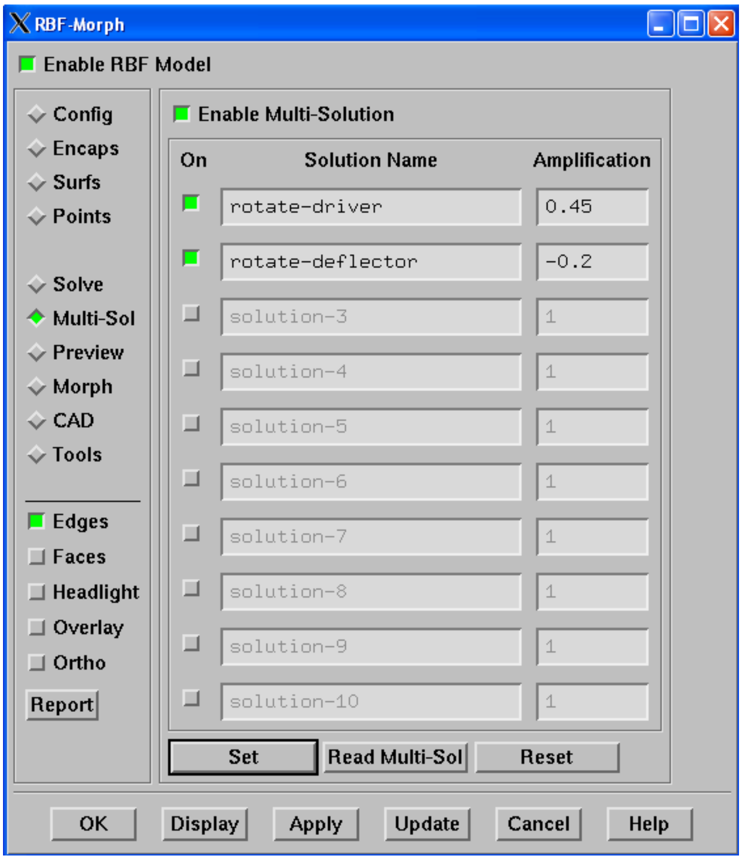

Figure 2: GUI of RBF Morph, Multi-Sol Panel. Up to ten modifiers can be combined using the GUI. The effect of the combination can be previewed on a particular area or can be imposed to the mesh (parameters can be tweaked several times thanks to the undo capability).

4. EXAMPLES

Some morphing examples are presented in this section with the aim to show the potential applications of RBF Morph.

4.1 Motorbike Windshield Optimisation

In this example, described in detail in [1], the effect of the angle of the adjustable deflector mounted on a Variotouring windshield is evaluated.
The RBF Morph add-on has been used to deform the original CFD model considering three deforming actions:

- changing of driver height;
- changing of driver position acting on the hunching angle;
- adjustment of the variotouring acting on the deflector angle.

The set-up stage for changing driver angle (or height) starts with the definition of an encapsulation box (Figure 3 left). Encapsulation domains of various shape (box, sphere and cylinder) can be used to limit the action of the morpher. For complex shapes the encapsulation domain can be defined combining an arbitrary number of such shapes (only the effective envelope will be used to locate source points). The number of points located on the surface is defined imposing proper point spacing. The effect of encapsulation is to give a near zero solution on the boundary (in fact zero value is imposed only on the source points, the zero values in other points on the encapsulation surface depends on spacing); furthermore the geometrical information are used to apply the morph only to the mesh nodes that fall inside the encapsulation domain. Moving encapsulation are also available (not used in this example): they work with a similar manner of encapsulation domains but prescribe a simple deformation field (i.e. rigid motion or scaling) inside the encapsulation and move the source points on the boundary accordingly. This means that the morpher action is applied only to the nodes contained inside the encapsulation domain and outside of the moving domains.

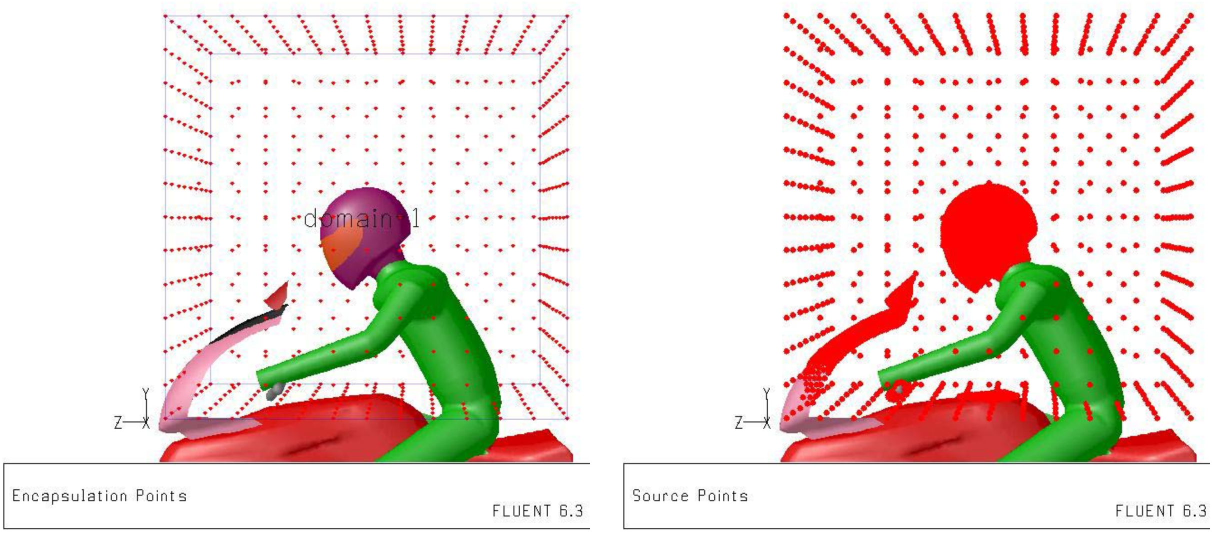

Figure 3: Set up step of RBF Morph. The morphed action is limited in the box region "domain 1" (left). The motion of the surfaces inside the encapsulation domain (right) is imposed to the points on the windshield (fixed), the fairing (fixed) and the helmet (moving).

To complete the set-up, two sets of source points on the surface are defined. The first one is composed by all the mesh nodes that belong to the helmet whereas the second one is composed by all the nodes on the bike and on the windshield. As can be observed in Figure 3 (right), only the nodes that fall inside the domain are selected (i.e. the encap domain, as the optional selection encaps, limits the action of the "on surface" selection). For the first set a rigid movement is imposed (a rotation about driver ankles or a displacement along driver neck) whereas for the second set a zero rigid movement is imposed to preserve the original shape of the bike components. The remaining nodes that fall inside the domain (i.e. the fluid and the body of the driver) remain free to deform under the action of the morpher. Before accepting the solution a preview of both cases has been examined (see Figure 4 and 5). After the preview the worst combinations of the parameters (i.e. maximum driver rotation for maximum and minimum driver height) have been tested, obtaining in both cases an acceptable quality mesh.

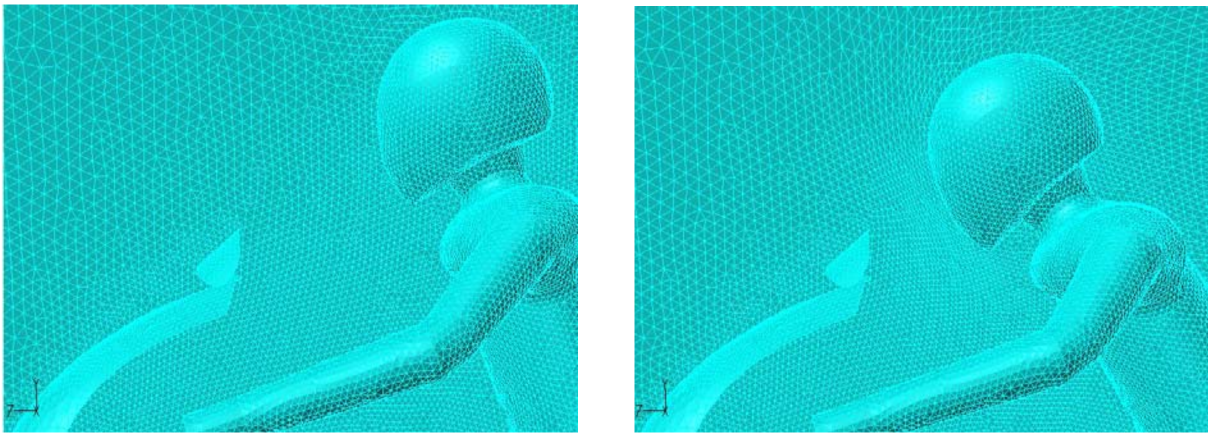

Figure 4: The mesh is morphed to change the driver angle of 15 degrees with respect to vertical axis

Figure 5: The mesh is morphed to change the driver height (5 cm), note that in this case the 15 deg hunched driver configuration has been used as the starting mesh.

4.2 F1 Front wing tuning

In this example an academic model of a F1 wing is used. The CAD model has been defined using the rules of the 2007 Formula 1 Championship (Figure 6).

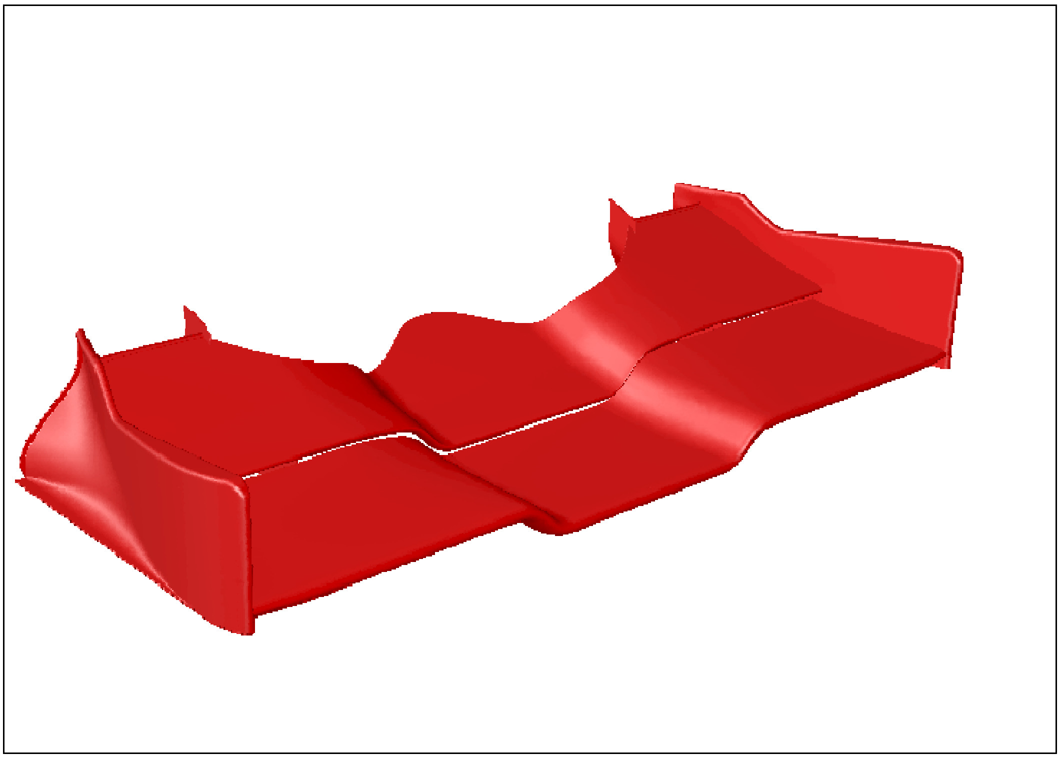

Figure 6: surface mesh of the F1 front wing.

To give an idea of potential use of RBF Morph, four cases have been tested to modify the wing set-up and shape:

- changing the flap angle (rigid rotation about its leading edge);
- changing the elements shape prescribing a rotation of the central portion around the main plane trailing edge;
- changing the elements shape prescribing a vertical displacement of the central portion around the main plane trailing edge;
- changing the elements shape prescribing a vertical displacement of the end plates;

In this section only the second case is described in detail. The modifier has the aim to rotate the central portion of the wing leaving unaffected the surfaces at the tip of the elements. This effect can be obtained limiting the action of the RBF Morph by means of a domain encap; the rotation of the central area is prescribed using a moving encap and imposing the desired rotation axis and baseline angle (the modifier can be arbitrarily amplified).
Box encaps are suitable for this task; they are represented, together with resulting source points, in Figure 7.
The effect of the modifier on the central portion is represented in Figure 8 where a preview of the internal mesh is overlaid to the original mesh shape. It is interesting to notice that the wing profiles and the boundary layers in the central portion are fully preserved by this kind of modifier. The portion of the wing surface that falls between the domain encap and the moving encap is gently deformed by the smoother (in this case the bi-harmonic kernel has been adopted). The shape of this deforming region can be controlled acting on the radial basis function type. In this case a two step procedure is recommended: a first step is used to define a free surface modifier only, while a second step is then used for the smoothing of volume mesh with the bi-harmonic kernel to guarantee the best quality.

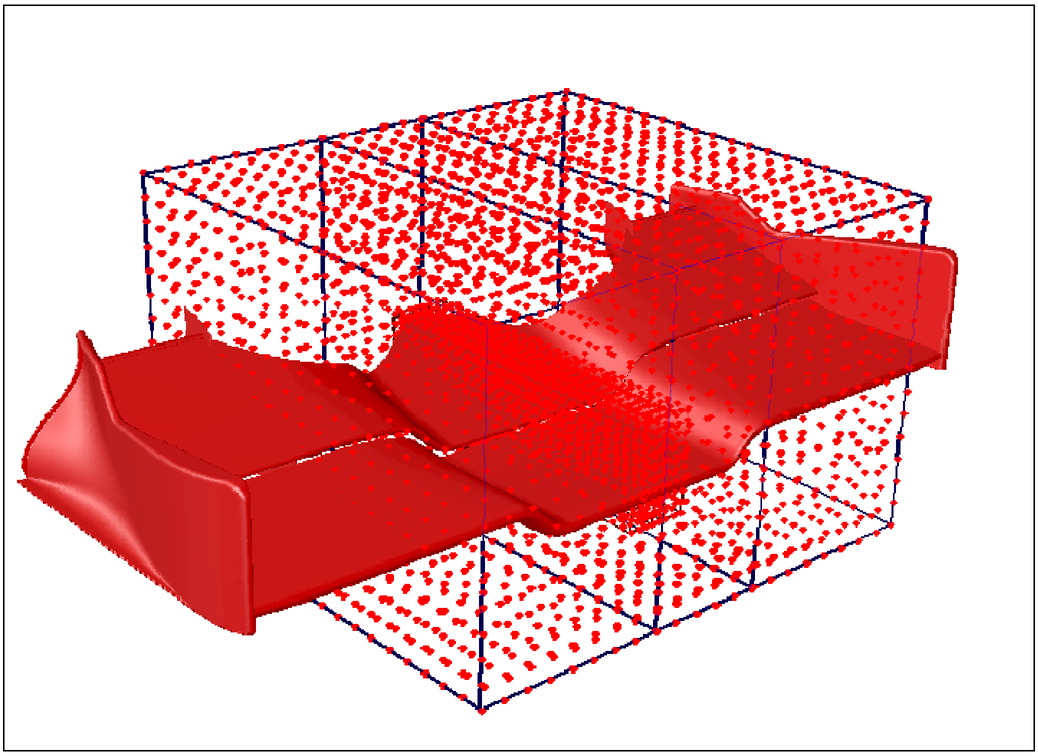

Figure 7: source point definition by means of domain and moving encaps.

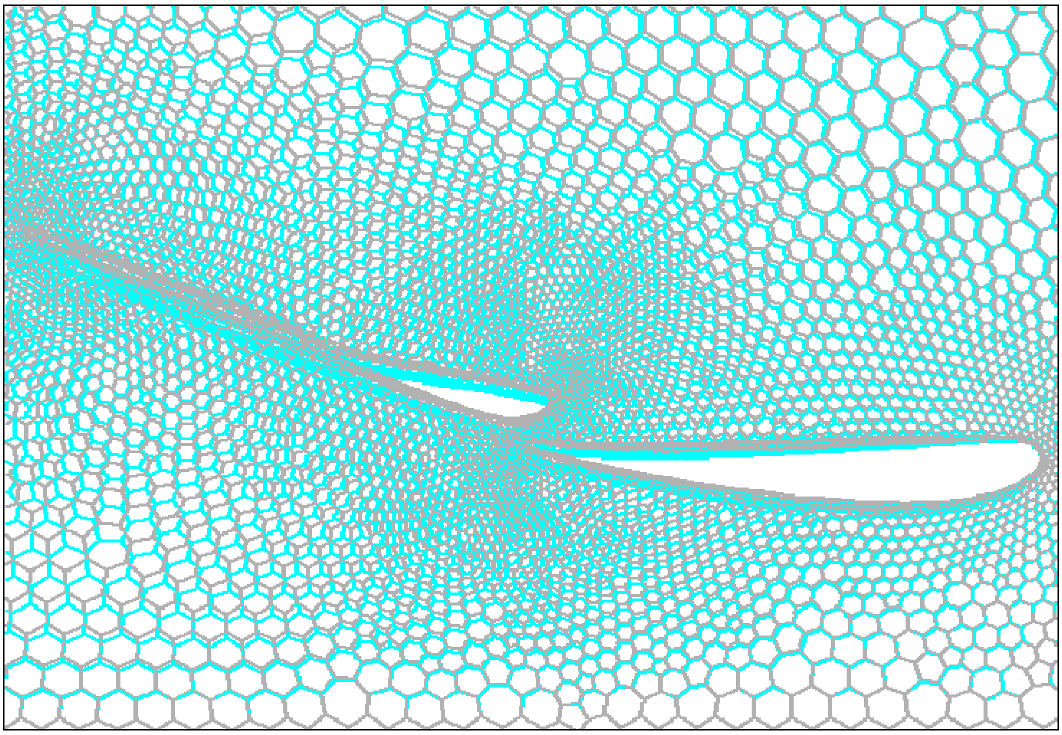

Figure 8: preview of morphing action on the symmetry plane.

5. CONCLUSIONS

In this paper the tool for CFD optimisation RBF Morph has been presented. The tool has proven to be very useful for two industrial applications: a motorbike windshield and a F1 front wing. Several modifiers have been tested considering rigid movements and surface deformations. For all the tested cases a good mesh quality has been always obtained for a wide range of modifiers. The results obtained not only prove how the new technology of RBF Morph is flexible for shape control and robust for mesh smoothing, but also clearly indicate a high level of maturity for complex and large industrial problems.

6. REFERENCES

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