VOLUMETRIC MESH MOVIMENT GUIDED BY GEOMETRIC INFORMATION

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Abstract. *This work describes IDMESH, a method for handling meshes for CFD aircraft design applications. IDMESH allows modifing a 3D model according to new information provided on a set of 2D profiles of the 3D model. The profiles are obtained from the intersection of cutting planes with the aircraft's wing. The profiles geometry can be modified by, for instance, inverse design process. To avoid mesh regeneration every time the geometry changes, we use Dynamic Mesh. Before moving the volumetric mesh, it is necessary to treat its boundaries (surface meshes) first. The process starts by modifying the wing geometry and then its adjacent surfaces. The modification of the wing geometry is acomplished by interpolating displacement vectors on the wing's vertices. These vectors are obtained from the modified set of profiles. When the wing geometry is modified, the elements placed on the wing/fuselage junction can become invalid. In order to fix this problem, we propose two new methods based on dynamic mesh: the Elastic Shape method and another based on conservative springs. The first method moves the vertices while trying to preserve the original shape.The latter, on the other hand, changes the shape. After the surface mesh movement, an standard elastic mesh method is used in order to move the volumetric mesh.*

Keywords: *mesh movement, dynamic mesh, elastic shape, unstructured volumetric meshes*

1. Introduction

The traditional way of designing aircraft wings requires many calls to a flow solver. These calls compute fluid properties such as pressure and drag distribution around the wing's geometry. These properties are used to feed the wing optimization process. The interaction solver/optimization can be a time consuming process because it may need hundreds of runs. The number of runs can be reduced considerably if the inverse design process is used.

Three pieces of information are needed to run the inverse design over an airplane's wing: (1) the initial description of the wing geometry; (2) a set of pressure distribution over the wing; and (3) a user defined target pressure distribution. The difference between the pressures is used to calculate the perturbations that should be applied over the wing geometry.

In this work, we are interested in providing an approach to carry the results produced by the inverse design in a 2D context over to the full 3D airplane model. The fluid solver runs on a volumetric mesh defined around the airplane's model. On this mesh cutting planes are defined which are perpendicularly lined up with the wing. The inverse design runs on 2D meshes located on those cutting planes in order to modify the wing section curves. We will use in the rest of this text the term profiles to refer to these curves. Figure 1 illustrates how this process takes place.

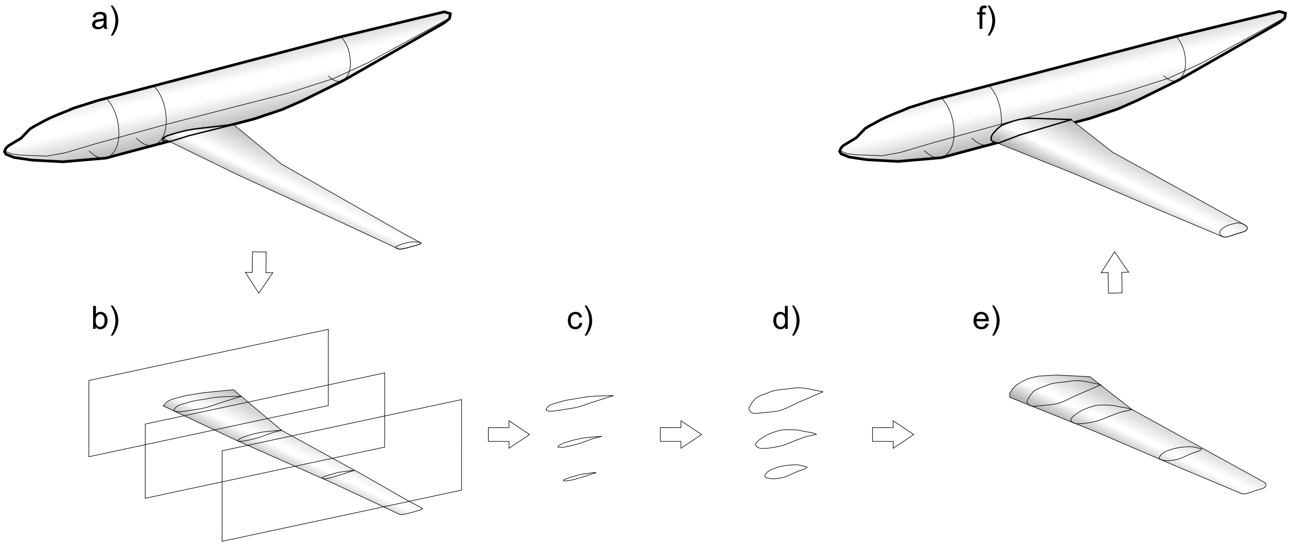

Figure 1. Integration 2D/3D; (a) the airplane surface model in 3D; (b) three cutting planes intersecting the wing; (c) set of profiles (2D) generated by the cutting process (old profiles); (d) the inverse design modifies the geometry of the profiles (new profiles); and (e) the geometrical information is carried to the 3D model.

It is important to notice that there are two sets of profiles. One of them is located on the original wing and the other is generated by the inverse design and will define the new wing geometric description. These two sets are called *old profiles* and *new profiles* respectively. Note that the airplane geometry is given by a 3D surface mesh and the new geometry of the wing is given by 2D curves (*new profiles*). These curves refer to the wing only, carring on information about the other parts of the airplane.

The mesh defining the airplane geometry is derived directly from the volumetric mesh, i.e. from its boundary, and shall be called *surface mesh*. So we handle two types of meshes: one composed of triangles and the other composed of tetrahedrons.

In order to link the inverse design to the flow solver, modification of both the airplane's geometry and the volumetric mesh are necessary. For this purpose, we developed an approach based on interpolation of displacement vectors and dynamic mesh, the latter is applied to both surface and volumetric meshes.

2. Review

In many applications, including shape optimization, the mesh domain may go through small changes at each step. One way to deal with these changes is by generating a new mesh at each step. However, this may be cumbersome, time consuming, and the new mesh will barely have the same number of nodes and connectivity. Therefore, remeshing does not seem to be a good choice in this case. Dynamic mesh, which is the basis of this work, is one approach that modifies the original mesh while preserving its initial connectivity, thus it seems to be a better choice.

Dynamic mesh is based on spring analogy, which consists in placing fictitious springs upon each mesh element. Whenever the mesh domain is changed, the springs are activated and move the vertices to some new equilibrium state. There are many approaches for doing dynamic mesh depending on the way the springs work and where they are placed.

[1] presented a mesh deformation algorithm that handles unstructured meshes by placing springs on the edges. Blom in [2] provided a detailed analysis of the spring method and draws an analogy between the spring method and elliptic partial differential equation approach for structured mesh generation. [5, 6] proposed modifications to the spring analogy in order to introduce torsional springs in the system. While longitudinal springs control edge lengths, torsional springs control angles. Initially, Farhat in [5] proposed the two-dimensional torsional springs model. This model was later improved to the three-dimensional case [4, 3]. Murayama in [8] proposed a simple, but robust, torsional springs model designed for dealing with large deformations in 3D domains.

Sadri et al. in [9] proposed an approach to couple inverse design with 3D fluid solver using grid deformation on structured meshes. To move the mesh, Sadri et al. need the block information used to generate the structured grid. The block information permits that the deformation process be applied only to the blocks surrounding the wing geometry. The deformation on those blocks is based on algebraic meshing techniques [7]. After block movement, the grid nodes are displaced by interpolation. Although Sadri et al. [9] and our work deal with the same problem, they handle different mesh types (unstructured and structured) and use different approaches to treat the volumetric mesh. Our approach is described in the following sections.

3. Modifying the model geometry

We constrain the scope of this paper to the treatment of simple models that are composed of just fuselage, wing, trailing edge and wingtip. The surface cells that compose each model component are separated out in different sets called *family*. For instance, the wing family contains all surface mesh cells located over the wing. The family concept is important because it allows applying a specific method to each component. Figure 2 depicts a aircraft model divided into four families.

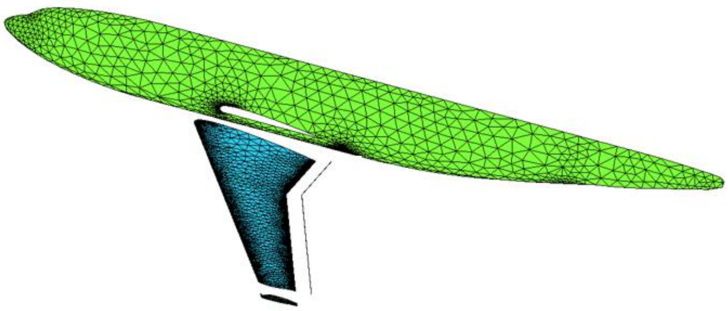

Figure 2. Aircraft model composed of four families (carenage, wing, trailing edge and wingtip).

The transference of geometric information from *new profiles* (2D) to the airplane model (3D) is carried through in stages. The wing family is firstly modified and then the families adjacent to it are processed one at a time.

3.1 Changing the wing by displacement-vector interpolation

Displacement-vector interpolation is the method used to geometrically reconfigure the surface mesh. As previously pointed, instead of acting on the geometry description, the approach taken in the present work is to reshape the surface mesh. This is acomplished by updating the vertices coordinates while preserving the mesh topology. Although, the displacement vector interpolation approach is robust and flexible from the geometric point of view, it can, in certain cases, produce invalid elements. These are delt with by the elastic shape method. The displacement-vector interpolation method is divided into three steps. The first step ensures that the corresponding profiles from the old and the new sets have the same number of vertices. This step adds or removes vertices from the old profile as needed. It also guarantees that the size of elements, in both profiles, follows approximately the same distributions along their length. The next step defines an ensemble of vectors called displacement vectors. These are simply the vectors transforming the old profiles into the new ones, and they establish a one-by-one relation between the old and the new profile vertices. The quality of the results from this step depend on the work done in the first step. The final step interpolates the displacement-vectors on the vertices of the surface mesh, employing a 3D least square method with polynomials of degree up to two. The interpolated vector will define a change in coordinates for the related vertex in the surface mesh. On doing this, the method tries to reshape the geometry of the 3D surface mesh based on geometric information extracted from the 2D profiles. After modifying the wing, the aircraft geometric treatment is continued by moving the other model parts.

The geometric changes on the wing can cause imperfections in the junctions with its adjacent components. Figure 3 illustrates the problems. In order to remedy these problems, it is necessary to apply specific correction tools for each family connected to the wing family, i.e. carenage, trailing edge, and wingtip families. All tools are based on dynamic mesh as can be seen on the next three sections.

3.2 The trailing edge (TE) correction

Considering the TE family alone, its boundary is a curve, called ς_{TE}, with parts belonging to the TE family and to the wing family simultaneously. Since only the vertices on wing family were moved so far, just a part of ς_{TE} was moved too. This partial movement of ς_{TE} may induce an undesired deformation on the TE geometry, as illustrated in Figure 4.

It is known that the standard dynamic mesh keep the nodes on the boundary stationary. Since just part of the trailing edge boundary was moved by the wing reconfiguration, the boundary should be processed individually. Therefore, the standard dynamic mesh is not a good choice in this case. In order to remedy this problem, the trailing edge correction takes

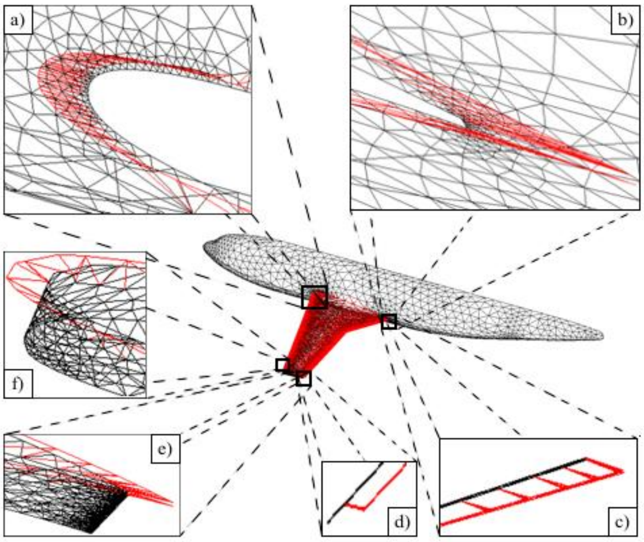

Figure 3. Imperfections on the surface mesh caused by changes on the wing family geometry; the model surface is shown before (in black) and after (in red) wing family deslocation. Carenage (a and b), trailing edge (c and d) and wingtip (e and f) are detailed shown.

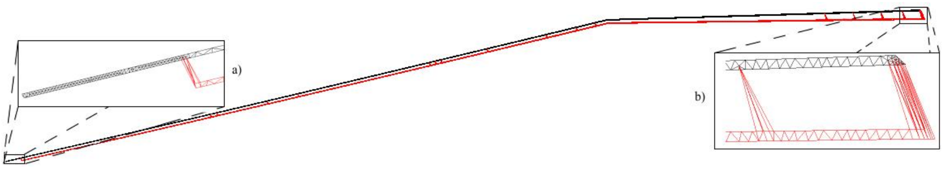

Figure 4. Trailing edge geometric problem caused by wing family movement; the trailing edge surface is shown before (in black) and after (in red) wing family deslocation.

two steps: (1) correction in ς_{TE} and (2) correction in trailing edge surface. These two steps are performed by applying the one and two-dimensional standard dynamic meshes, respectively. Figure 5 illustrates the trailing edge correction.

3.3 The wingtip correction

The difficulty in dealing with the wingtip rests on the fact that it can assume different shapes, varying from simple plane surfaces to complex winglets. In many cases, the deformation of the wing requires changes on the wingtip geometry. Therefore, any technique for moving the wingtip must also change the original wing shape. A good approach is one that makes changes on the wingtip while trying to preserve as much as possible the original wing shape. For this purpose, we developed a method based on dynamic mesh techniques which includes a new type of spring named *conservative spring*.

The network of springs in this case is composed of both longitudinal and conservative springs. The longitudinal ones are attached to the edges and work in the same manner as in the standard dynamic mesh. The conservative spring is a special case of the longitudinal one, but it is related to each single vertex v; it has one of its ends fixed on the moving vertex and the other end fixed on the same vertex at its starting position, i.e, the same vertex before its motion. Therefore, at the beginning, all conservative springs have null length. To each wingtip family vertex (excluding the ones on the boundary) is attached one conservative spring which prevents the vertex to go too far from its initial position. The degree of deformation on the surface is given by the stiffness coefficient of the conservative spring. These coefficients are provided by the user and can vary from 0.0 to 1.0. The greater the coefficient, the more deformable the surface is. Figure 6 illustrates the wingtip correction process.

3.4 The carenage correction

The carenage treatment is different from the previous ones. Firstly, it is not a planar surface, so the standard dynamic mesh may not be applied as it was in the TE. Secondly, though it is a curved surface as the wingtip is, its shape must be preserved instead of deformed. Therefore, to correct the deformations caused by the wing modification it is necessary to move the carenage vertices while keeping its geometric shape. For this purpose we developed a new technique named *Elastic Shape* [10]. The idea behind the elastic shape is quite simple, endeed it just adds a new step to the standard dynamic mesh, which projects the vertex back to the surface after the motion determined by the springs. In another

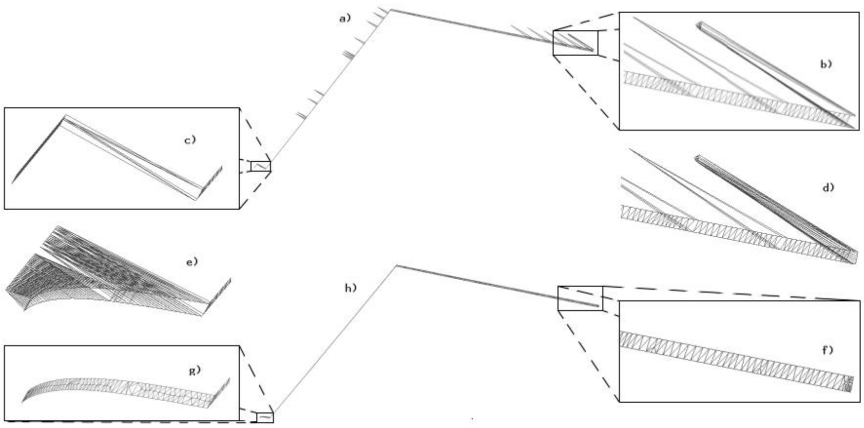

Figure 5. Correcting the trailing edge family; (a) the trailing edge surface after wing displacement; (b) and (c) zoom on the ends of the trailing edge; (d) and (e) after boundary correction; (e) and (g) after surface correction and (h) final result.

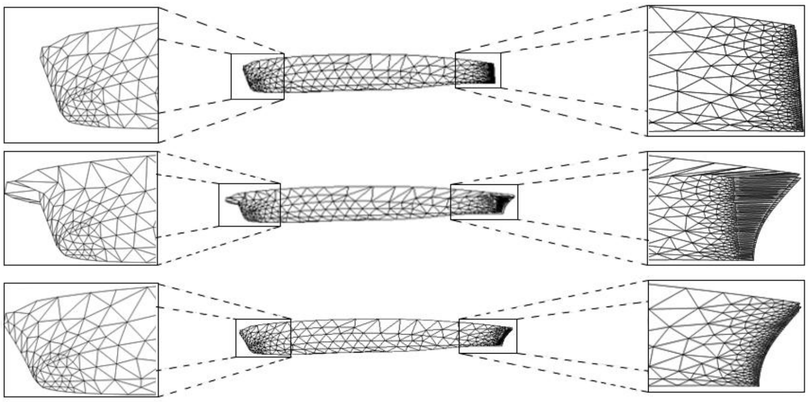

Figure 6. Correcting the wingtip family; the wingtip surface before (a, a1, and a2) and after (b, b1, and b2) wing displacement; (c, c1, and c2) the wingtip after correction.

words, whenever a vertex is displaced by the dynamic mesh, it is immediately projected back onto the original surface. Figure 7 illustrates the carenage correction process.

After all corrections on the surface mesh, we turn to the volumetric mesh where the standard dynamic mesh using longitudinal [1] and torsional springs [8] are applied.

4. Results

The model we have used for producing the results discussed here is schematically shown in Fig. 2. The volumetric mesh is composed of 96693 tetrahedrons and 22402 vertices. Although it is a simple model, it adequately serves to our purposes since it requires all the different processing steps discussed in section 3. to ensure mesh quality and further usability after modifications on the profiles.

In practice, once the inverse design subroutine is called, it introduces deformations on the profiles, that are generally small in scale when compared to the model. Nevertheless, with the intent of emphasizing the robustness of the method when dealing with complex meshes as those of aircraft simulations, we have employed deformations larger than the usual. Figure 8 depicts the *old* and *new profiles set* used to produce the results presented here.

Handling unstructured meshes calls for the use of two types of data structure, SHE (Surface Half-Edge) and HF (Half-Face). The former is used for representing the surface mesh and the latter for representing the volumetric one. The SHE data structure implements the family concept, which is important for applying the appropriate geometrical treatment to specific parts of the aircraft, as discussed section 3. The operations upon families include traversal over all triangles, vertices and boundary curves.

Even though the main applications where our methodology shall be used are related to inverse design problems, in this paper we are mainly concern with geometrical results. Putting it in other words, we do not simulate the flow around the aircraft using the modified mesh to verify if it is a suitable mesh. Instead, we analyze the quality of the mesh elements using the following quality parameter:

$$\beta = V/l_{max}^3 \qquad (1)$$

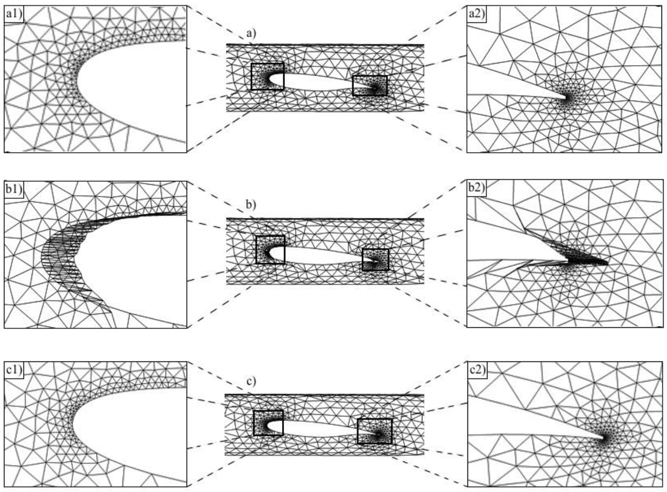

Figure 7. Correcting the carenage family; the carenage surface before (top) and after (middle) wing displacement; (bottom) the carenage after correction.

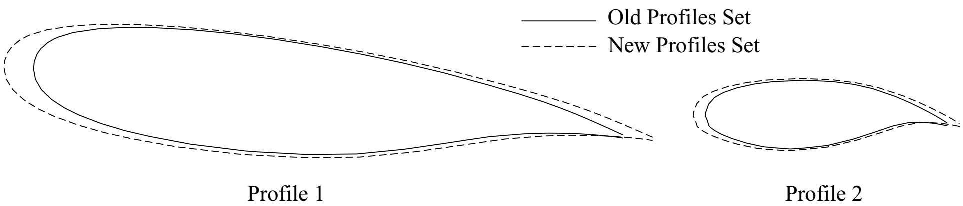

Figure 8. The *old profiles* and the *new profiles*, each one composed of two curves related to two cutting planes.

where V is the tetrahedron volume and l_{max} is the largest tetrahedron edge. The greatest the value of β, the better the quality of the tetrahedron. In a equilateral tetrahedron the value of β is around 0.11785. Negative values of β indicate that the tetrahedron have been inverted meaning that one tetrahedron face was crossed by one of its vertices.

Table 1 displays quality values used for acessing the quality of the results. Let β_{min} and β_{max} denote respectively, the smallest and the largest β values for the analyzed mesh; and β_{med} denote the arithmetic average of all $/beta$ values corresponding to the elements in the mesh. The number of invalid elements are also displayed in table 1. The entries in the table were acquired from the same mesh on four different stages. The stages occur successively in time and each of them adds changes upon the mesh from the previous stage. The stages are:

I. *Original Mesh*: the mesh at the start, i. e., without any deformation (stage 0).

II. *Deformed Mesh*: the mesh after wing deformation by displacement-vector interpolation (stage I). No correction on the wing adjacent families (surfaces).

III. *Corrected Mesh*: the mesh after applying our approach of this work, to correct the deformations on the boundary (surface mesh) of the *Deformed Mesh* (stage II). At this stage, the dynamic mesh has not been applied on the volume yet.

IV. *Final Mesh*: the mesh after the full correcting process, including the use of the volumetric dynamic mesh on the *Correct Mesh* (stage III).

Carefully observing the entries of table 1, it is possible to note that in spite of the domain undergoing a large deformation, the technique described in this work has been capable of correcting all the invalid elements. Observe also that the average quality of the elements (β_{med}) does not get worse when compared to the original mesh. This can more easily be verified in the Fig. 9, where a detailed quality measurement distribution, considering the *Original Mesh* and the *Final Mesh*, is presented. The graphic shows that the quality of the mesh final is almost the same of the original one.

5. Conclusion

In this paper we have presented an approach to link a two-dimensional inverse design tool with a three-dimensional flow solver. The inverse design tool, named IDesign, works on a set of profiles, which are, in fact, curves obtained from the aircraft's wings by cutting planes. The profiles geometric information is transported to other parts of the aircraft

Table 1. Quality values (ep. 1) of the volumetric mesh related to the model showed on Fig. 2. The quality values were measured on each of the four stages cited above.

Stages	β_{min}	β_{max}	β_{med}	Invalids
Original Mesh	0.008182	0.109553	0.0361731	0
Deformed Mesh	-0.073921	0.107143	0.0236085	17160
Correted Mesh	-0.073921	0.107143	0.0223170	18441
Final Mesh	0.004392	0.107143	0.0361874	0

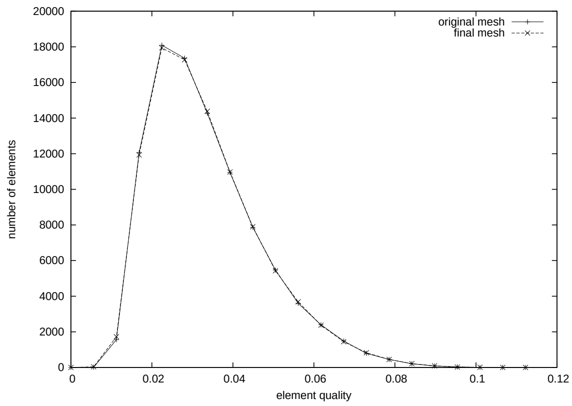

Figure 9. Element qualities ($\beta = V/l_{max}^3$) in the *Original Mesh* and the *Final Mesh*.

by interpolation of displacement-vectors and dynamic meshes. The former is used over the wing and the latter over its adjacent surfaces (trailing edge, carenage and wingtip). The process of modification of the geommetry follows a strict sequence: starts from the wing, then adjusts the trailing edge, and, finally, corrects the wingtip and carenage.

In order to apply dynamic mesh over the model, we had to make modifications to the standard method. We developed a new type of spring, named *conservative spring*, which allows using dynamic mesh to modify the geometry of a surface while trying the keep the overall shape. The degree of deformation is provided by the stiff coefficient of the *conservative springs*, which is a user defined value raging from 0.0 to 1.0. The other approach of dynamic mesh developed by us is the *dynamic shape*, which moves surface's vertices upon the surface itself. This method tries the keep the original surface geometry as much as possible. These two new types of dynamic mesh have shown to be useful tools to handle geometry of surfaces. After all surface corrections, the standard dynamic mesh is used to move the volumetric mesh.

Even though the principal motivation for the development of the approach described here was to link the inverse design and the flow solver, the same approch may be used in a variety of applications for which the transport of geometric information from curves to surfaces is required. Specific mesh-element-quality criteria was used to demonstrate the suitability of the present approach as tool for correcting meshes. To test the robustness of the method, we have submitted the model to larger deformation than those that may be used in practical cases. The results showed that the overall mesh quality is consistent with the deformation applied, i.e., the mesh quality decreases as expected while the proportion of bad and good elements is maintained, as depicted in the Fig. 9.

In future developments we aim at extending the technique described in this work for handling aircraft models of increasing complexity, including structures such as: FTFs, pylon/nacelle and winglets. Furthermore, we plan to be able to deal with hybrid meshes, i.e., volumetric meshes composed of tetrahedrons, prims, pyramids and hexahedrons. This implies that the surface mesh may be composed of triangles and/or quadrilaterals.

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