New approach for accurate, robust morphing of CAD geometries

Facilitates bi-di transfer between analysis-test-manufacture and design

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The following article presents an automated approach to the morphing of CAD geometry based on the results of simulation. After breaking down the morphing process into its component steps: matching, deformation, and rebuilding, some industrial examples are described. This article also discusses some of the issues associated with accurately rediscovering the mesh geometry parentage and how this can affect the quality of a morph. The morphing process is demonstrated using an example blade model and the NASA Common Research Model.

Many computer-aided engineering (CAE) analysis applications can generate a displaced mesh to represent the deformed shape of a component under specific operating conditions. CAE simulation is increasingly used to generate optimized geometric definitions of components where the output commonly takes the form of a deformed mesh[1]. Multi-disciplinary analysis and automatic shape optimization are two important scenarios where the deformed mesh from one analysis needs to be used as the basis for a second, dependent CAE analysis[2]. Converting the deformed mesh to an accurate deformed computer-aided design (CAD) geometry may also be required for further design work and ultimately manufacturing.

A common approach for deriving acceptable CAD models from deformed component shapes is to reverse engineer a new geometric model from the displaced mesh. This typically involves using approximate curve- and surface-fitting algorithms to match selected regions of the deformed outer skin of the mesh. However, this approach frequently suffers from issues of accuracy and surface irregularities, and often results in geometry models with insufficient fidelity for use in CAD systems, or that are unsuitable for CAE re-meshing. Fig. 1 shows examples of least squares surface fits to a highly curved wing-tip mesh with the resulting undesirable deformed surfaces that can be created.

This article describes a more accurate approach which morphs the original CAD geometry to match the displaced mesh from analysis. Using the original CAD curve and surface definitions as the basis for the morphed geometry ensures better accuracy, smoothness

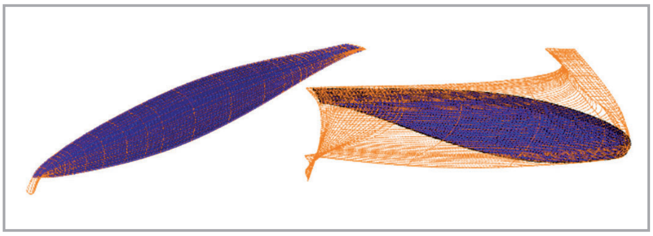

Fig. 1 - Poorly fitted least squares non-uniform rational basis spline (NURBS)

and continuity. The process also provides significantly better support for sparse deformation data where the traditional least squares fitting approach can struggle to produce usable geometry.

This advanced geometry morphing process supports the import of deformation data from various sources and results in an accurate morphed version of the original CAD geometry. Using this process, it is possible to accurately deform original CAD geometry based upon CAE analysis results.

Mesh-to-CAD matching

Before the morphing of the CAD geometry can begin, the undeformed mesh needs to be related back to the original CAD geometry and its node parentage needs to be determined to ensure that the nodal displacements from the analysis are applied to the correct areas of the CAD model. Most meshes do not carry the geometry parent information, so this needs to be recovered by matching the mesh to the geometry.

The initial mesh-to-geometry matching algorithm was based on a simple geometric proximity algorithm, projecting nodes onto the CAD model edges to partition the mesh. This method works well for meshes that are perfectly aligned with the geometry, however many meshes are not. A new matching algorithm that can handle a wide range of industrial meshes has been developed to deal with the matching failures caused by the misalignment of the mesh and CAD.

The new matching algorithm makes use of both geometric and topological data to match the mesh to the geometry. The algorithm traces out the edges of the CAD topology onto the mesh; the tracing of an edge onto the mesh is called the edge image. These edge images are used to segment the regions of nodes and elements which are then parented to appropriate faces in the CAD model.

The tracing process does not require the mesh to have nodes exactly on the CAD edges, meaning that the matching is far more robust for misaligned meshes.

Fig. 2 shows a misaligned mesh where the top edge is aligned with the mesh, but the bottom edge is not and crosses several elements. It is possible to find an image of the bottom edge, but it requires a large matching tolerance.

There are cases where no unique images of the edges exist in the mesh, where the mesh topology does not match the topology of the geometry. These cases can broadly be divided into two groups: abstracted edges and virtual topology.

Abstracted edges typically occur in meshes near sharp faces or narrow regions. In these cases, the faces are so narrow that the mesh generator cannot position two distinct nodes on the opposite edges of the face, and so collapses them onto a single node, removing elements from the mesh to avoid making degenerate or

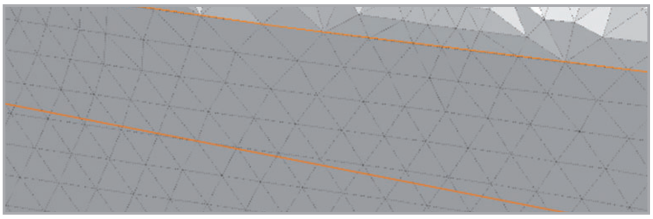

Fig. 2 - Misaligned mesh and topology

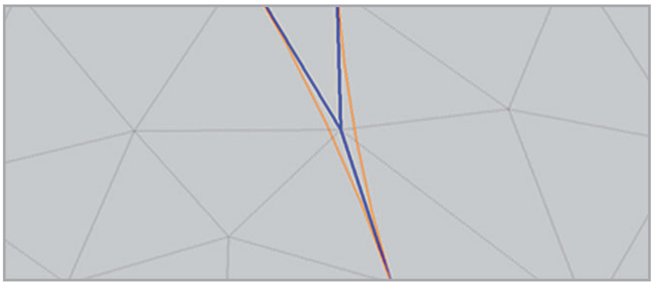

Fig. 3 - The CAD edges (orange) both use the same element edge (blue) in their edge images

poor-quality elements. Fig. 3 shows an example of an abstracted edge.

The matching algorithm does not require each edge image to be unique for every edge, allowing it to trace out two images from the same edge in the mesh, leading to a full match, even when face regions have been pinched into two distinct regions on the mesh.

Virtual topology (VT) consists of deliberately misaligned mesh spanning several elements and multiple CAD faces. This often occurs in regions of tight curvature or where there are many small CAD faces and the mesh generator cannot mesh the geometry with acceptable element quality. Fig. 4 shows an example of a mesh from a VT region.

In this case, it is not possible to determine the edge images and to match the mesh exactly to the geometry. The nodes within a VT region can still be parented to a unique face, but the elements cannot where they span multiple faces. The lack of element-to-face parenting results means there is insufficient information to morph the geometry, but it does allow for a mesh-to-CAD comparison based on node proximity only. The matching algorithm can discover the extent of the VT regions and identify groups of CAD faces that belong to the VT region. Future enhancements are

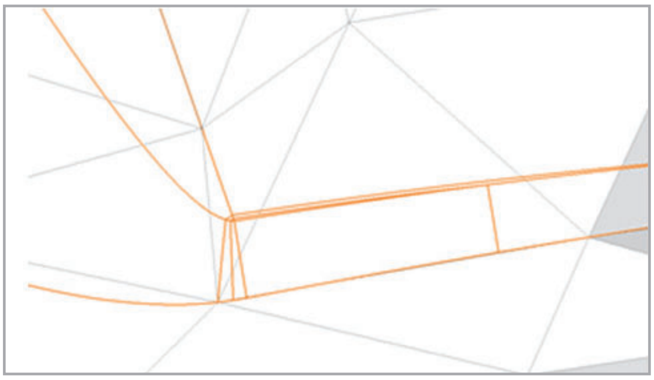

Fig. 4 - Mesh on a virtual topology region

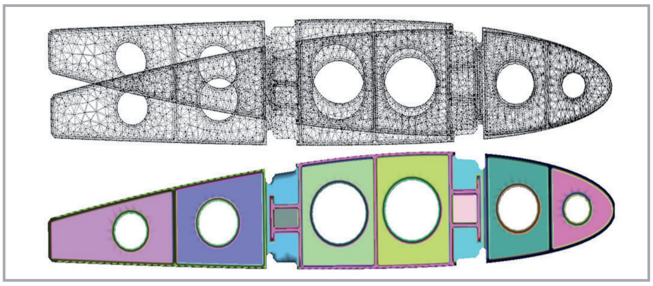

Fig. 5 - Large complex engine example showing matched regions in different colors

planned to enable nodal deformations to be interpolated from the VT region onto the edges and faces that they cover, thereby enabling morphing.

For morphing to provide valuable benefits in industrial use cases it is required to handle large CAD models with complex geometries and very large meshes. The limiting step in processing very large models is the mesh-to-CAD matching stage. The initial implementation, using just geometric proximity data, limited the matching process to working with a single body, or multiple bodies that did not touch. Coincident meshes from contacting bodies were too complex to untangle, and models containing several bodies could not be morphed as the deformation data could not be applied to the correct surface in touching regions.

Fig. 5 shows an example of a large mesh after CAD geometry/topology matching. The improved matching algorithm achieves greater robustness by making use of the topology of the CAD model and enables the contacting bodies and mesh to be correctly segmented and parented for morphing.

Performance is also significantly improved by the use of the CAD model's topology. The number of geometrical queries is greatly reduced, allowing the matching algorithm to run in a few seconds, compared to the original basic proximity approach which can require several hours.

The morphing process

Geometry morphing can begin once the undeformed mesh has been parented to the original geometry. The deformation vector field is first extracted from two twinned meshes. The first mesh is of the nominal CAD geometry in its undeformed state, and the second mesh is the deformed twin of the same mesh. The second mesh represents the desired deformed shape of the CAD, usually

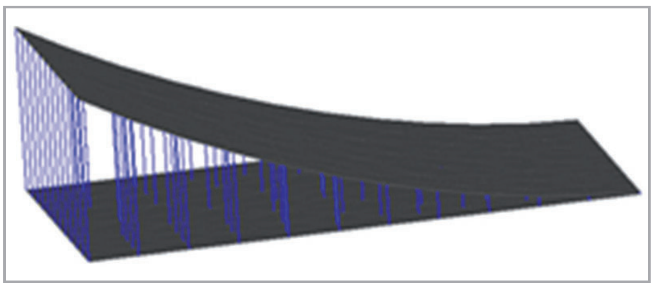

Fig. 6 - The deformation vectors between the twinned original and deformed meshes

the result of a simulation. Because the two meshes are twinned, every node on the undeformed mesh is paired to its equivalent on the deformed mesh. The deformation field is calculated from the difference between the two meshes. Each vector in the field will start at a node position on the undeformed mesh and point to the node's twin on the deformed mesh. Fig. 6 shows an example of a pair of twinned meshes and the corresponding deformation vectors.

The nominal CAD geometry must be defined as a standard CAD boundary representation (BREP). The curves and surfaces are required to be defined using NURBS. Any non-NURBS geometry is converted into a NURBS format prior to the morphing process.

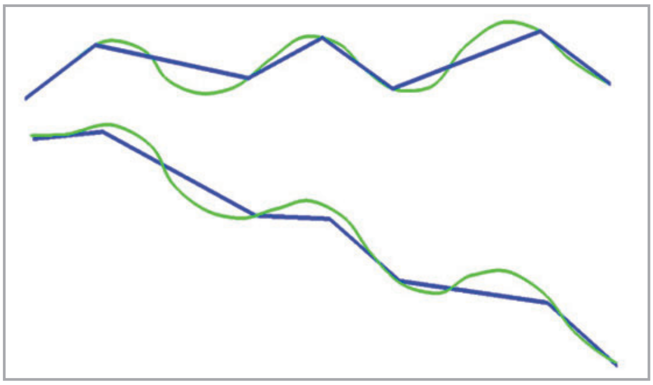

Fig. 7 - The top edge (green) is meshed by a sparse mesh (blue) and morphed into the bottom edge (green) using the deformed mesh (blue)

The first step is to morph the vertices of the CAD geometry by a simple translation through the relevant deformation vector derived from the parented nodes.
The second step morphs the edges that bound the faces of the CAD geometry. Each CAD edge has a string of matched nodes running along it, each node with its own deformation vector. These deformations are parametrized, and a curve is constructed from them using a least square fitter [3]. The resulting curve can be considered a 'delta' curve. The delta curve is then reconciled with the original CAD edge and is finally added to it to produce a new, deformed NURBS edge [4]. Fig. 7 illustrates the process of morphing a simple edge.

The key benefit of deforming using a delta curve is that it preserves any original design intent from the undeformed CAD edge. Fig. 7 shows that the oscillations in the undeformed curve have been carried over to the deformed curve, a benefit that simple fitting to the deformed mesh cannot achieve.

The morphing of the CAD edges reveals why accurately matching the original mesh to the original CAD is so important. If it is unclear how to deform the ends of curves because, for example, the mesh does not align well and was not matched correctly, then the morph will be poor. If a node was matched to the end of the edge but was not exactly on the CAD vertex, then, assuming the deformations are reasonably smooth, the morphing algorithm can

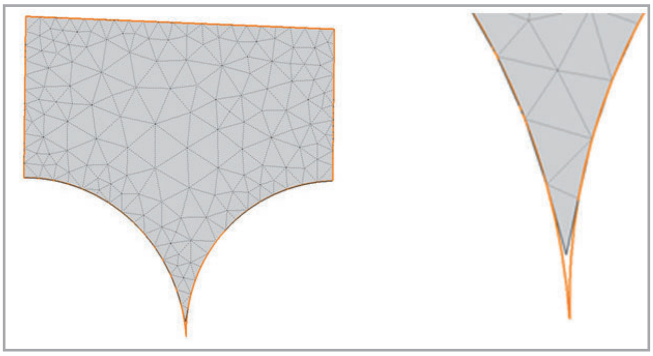

Fig. 8 - An example of where the image of a face in the mesh is smaller than the CAD face

interpolate/extrapolate an acceptable deformation for the edge ends. This ensures that all edge ends connected to a specific CAD vertex are deformed consistently and that the morphed model remains watertight.
The third step of the process morphs the embedding surfaces of the original CAD faces. The process of morphing the NURBS surfaces is similar to the morphing of the edges. A delta surface is constructed from the deformation field and then summed with the original CAD surface.

The morphing of surfaces is further complicated if the topology of the mesh does not exactly match the topology of the CAD geometry – for example, in faces containing cusps, where part of an edge has been abstracted by the mesh generator. These missing regions may lead to the region of the mesh parented to the face having a smaller area than the CAD face, as shown in Fig. 8.

All deformations that have been matched to edges of the face, including any partial or abstracted edges, must be fully included to ensure that the extents of face are fully deformed.

The final step of the morphing process is to construct new CAD BREP geometry from the newly morphed vertices, curves and surfaces. This step is relatively simple as all of the topological information is contained in the original CAD model. This topological CAD data, combined with a mapping from the undeformed to deformed entities, allows the construction of a new body.

It should be noted that due to this mapping, all the faces that appear in the original CAD will have a counterpart in the new, morphed geometry and that no faces will be lost or created.

The following sections describe the application of this morphing process to different industrial use cases.

"Hot" geometry from "cold"

Engine components may be designed in the nominal "cold" shape in CAD, which can be quite different to the "hot" shape they adopt within a running engine. The nominal cold shape is meshed and a thermo-mechanical finite element (FE) analysis is run to produce a displaced mesh that represents the hot shape of the component.

The challenge is to convert the deformed structural mesh back to a CAD model of the hot shape that can be re-meshed for the subsequent computational fluid dynamics (CFD) analysis of the running engine.
The CADfix morphing approach takes the original CAD model and accurately morphs the curves and surfaces according to the displaced mesh from the thermo-mechanical analysis. Fig. 9 shows the nominal CAD geometry of a cold blade, the initial undisplaced mesh of the cold geometry, and the displaced mesh after the thermo-mechanical analysis.

The undeformed mesh is matched to the original CAD geometry to establish which mesh nodes will be used to deform the CAD

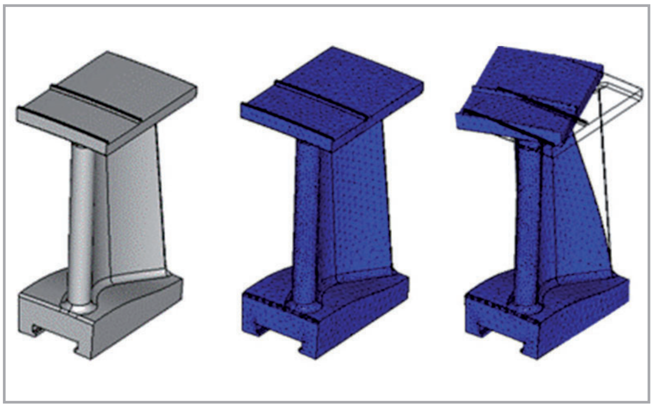

Fig. 9 - Original CAD, undeformed mesh and deformed mesh

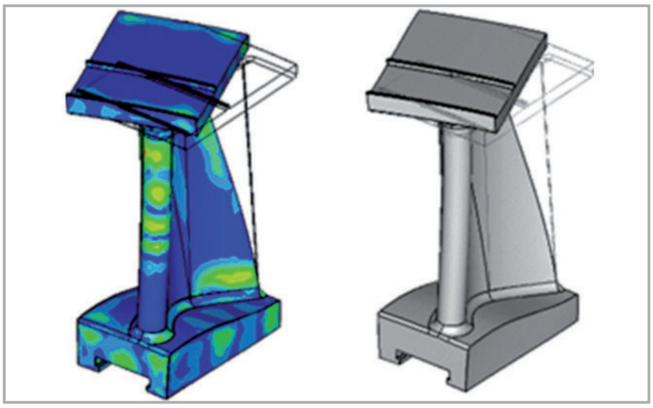

Fig. 10 - Morphed CAD showing fit error and the final CAD geometry

curves and surfaces. Once the mesh-to-geometry matching is completed, the mesh deformation vectors can be applied directly to the original CAD curves and surfaces to deform the geometry. The accuracy of the morphing process can be controlled via a user-supplied target-fit tolerance. Fig. 10 shows the results of morphing the blade geometry to match the displaced CAE mesh.

The resulting high-quality morphed CAD geometry can be exported to a range of standard CAD formats, ready to be imported and re-meshed for the subsequent CFD analysis.

Deformed wind tunnel geometry

Geometry deformations can come from sources other than analysis, such as physical measurement. The 6th AIAA Drag

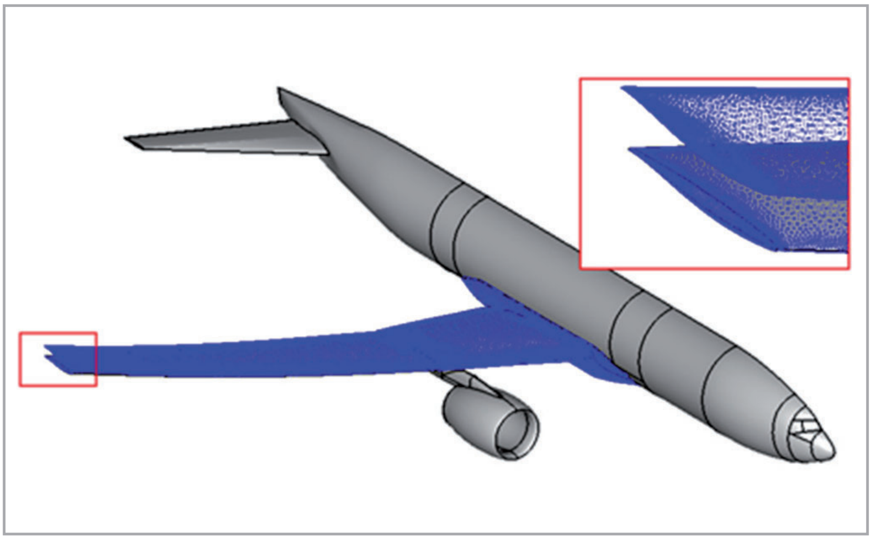

Fig. 11 - NASA CRM showing partial deformed mesh with extension into fuselage fairing

Prediction Workshop required the generation of a set of accurate and meshable deformed geometries for the NASA Common Research Model (CRM) [5] to match the aero-elastic deformations as measured in the wind tunnel.

The morphing process was extended to import NASTRAN skin meshes of selected regions (e.g. wing and belly fairing) and then to apply the deformations to the complex CAD surfaces with regions of very high curvature, such as the wing-tip. The CAD surfaces of the CRM are complex and preserving their initial design as much as possible was critical. By directly deforming the original CAD geometry, the design intent was preserved, and the deformations were smoothly applied.

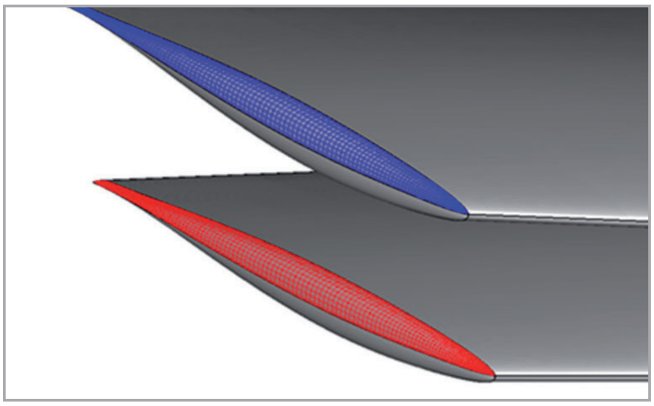

Fig. 12 - Close-up of complex wing-tip surfaces showing before (red) and morphed (blue) surfaces

In the case of the CRM, the original CAD geometry was only partially covered by the deformed mesh, which introduced additional CAD matching challenges. Initially, deformations were only defined for the wing surfaces, and after applying the morphing process it was observed that the junction between the wing and the fuselage had not been preserved correctly. Further investigation determined that for partial deformations it is critical that the deformation field around the boundary of the deformed region must have zero deformation. Without this condition, the morphing process tends to introduce lateral shearing at the junction.

To resolve this issue, the region of partial mesh was extended to cover the wing/fuselage junction, allowing the deformation field to smoothly decrease to zero at the interface with the fuselage. Fig. 11 shows the extended partial mesh that includes the wing/fuselage fairing.

The complex curvatures of the wing-tip surfaces proved challenging. Traditional least squares regeneration of a new geometry from the deformed mesh struggles with the combination of high curvature and low mesh density. The lower half of Fig. 12 illustrates one of the wing-tip surfaces before (red) and after (blue) deformation, clearly showing that the direct CAD morphing has preserved the complexity and integrity of the original CAD surface design.

Conclusions

Connecting simulation and test results into the design process, such that analysis truly leads design, offers potentially significant breakthroughs. The new approach outlined here for accurate and robust morphing of CAD geometry based on analysis results can facilitate the missing bi-directional transfer of geometry between analysis/test/manufacture and design. While there is more work to be done to ensure further automated handling of virtual topology, the morphing tool is already being used in an industry setting, with two industrial application examples being shown: one for cold-to-hot turbine blade deformation, and another for the aero-elastic deformation of aerodynamic shapes to reflect real world measurements.

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