Title:
**Automatic Hexahedral-Dominant Meshing for Decomposed Geometries of Complex Components**

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Introduction:
Generating good quality simulation models is a major bottleneck in the automation of simulation workflows, as it can often be the most time consuming task and can require extensive user efforts and skills. As a result, the use of simulation tools throughout the analysis cycle is not as prevalent as it could be, in particular at preliminary design stages, where the configuration is prone to modifications. Moreover, many analysis require the use of hexahedral (hex) elements in order to accurately analyse highly non-linear time-dependent events such as crash or fan-blade off, and no robust automatic hex-meshing tool is available yet for components of this type. The current industry standard for generating hex meshes consists in manually sub-dividing the design geometry into sweep-meshable sub-domains. Splitting the geometry using current geometry editing tools results in losses of information since the manifold structure cannot retain the interfaces between cells, and the user has to specify them manually in order to obtain conformal mesh.

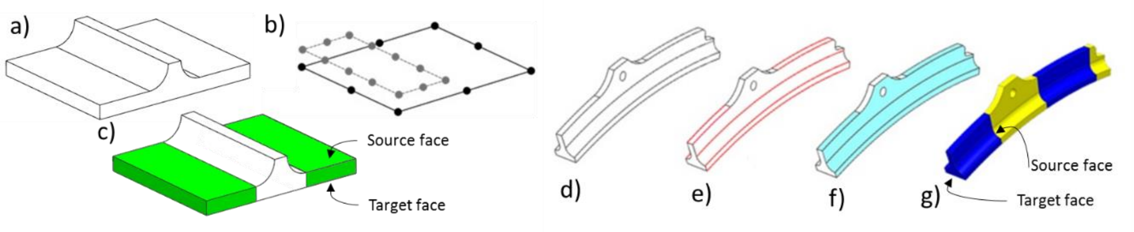


Fig. 1: Thin-sheet (left) and long-slender (right) decomposition: (a) candidate geometry, (b) discretized face pair, (c) two thin-sheet regions extracted in green, (d) candidate geometry, (e) long-edges identification, (f) 2 loops of long faces, and (g) two long-slender regions extracted in blue.

This work describes an automated approach for hex-dominant mesh generation for a CAD model, built on top of the automated approaches described in [2], [3]. This is a two-step approach to identify and isolate sweepable regions in a CAD model (Fig. 1). First, thin-sheets regions which have two dimensions larger than the third are extracted by interrogating and manipulating the pairs of bounding faces (Fig. 1(a-c)). In a second step, long slender regions, which have one dimension larger than the other two (Fig. 1(d-g)) can be extracted. To achieve this, nearly parallel long edges are first identified (red in Fig. 1(e)) using metrics based on aspect ratio to the bounded faces, then loops of long faces are identified to define long-slender bodies.

To enhance the process herein, the manifold decomposition is enriched by generating an equivalent non-manifold cellular topological representation. This representation uses virtual topology operations to track the subdivision history thus capturing information lost through the manifold decomposition, for example the interface in Fig. 3. In addition, each cell in the non-manifold cellular decomposition is assigned appropriate simulation attributes defined by the geometric reasoning tool used to dictate the decomposition. The enriched data-structure uses integer programming routines and adjacency information to automatically create a fit-for-analysis mesh with correct mesh controls and mesh-mating.

Main Idea:

*Overall process*

Proper management of analysis information is essential in order to successfully automate analysis workflows, especially when it involves many different software tools. In particular, the different geometric representations used in CAD and CAE packages make the mapping of entities challenging between them, since CAD systems use a manifold representation while many CAE systems use a non-manifold one. A face can only bound one body in a manifold representation, hence the interface entity between two bodies cannot be directly identified. In non-manifold structures two touching bodies can share a single face, which can be used to ensure a conformal mesh is generated at the interface.

The solution presented herein is an independent topological definition of the CAD and CAE representations, as depicted in Fig. 2. CAD and CAE representations are linked to one another in the common data structure to enable analysis attributes to be transferred between them. Geometry manipulations are carried out topologically within the data structure, facilitating the creation of a non-manifold analysis representation. The enriched data structure is then used to automatically derive the meshing recipe necessary to generate a hex-dominant mesh from the manifold decomposition.

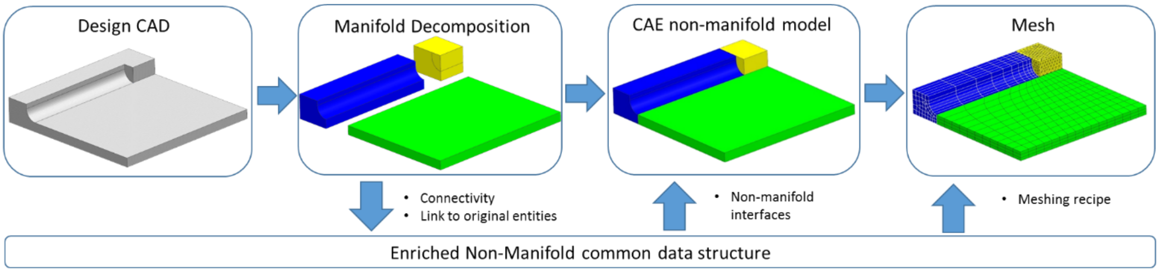


Fig. 2: Automatic hex-dominant meshing process using an external data structure.

*Capturing decomposition decision*

The proposed approach makes use of an external data structure based on a SQL relational database [4], to link different representations and store simulation attributes. A non-manifold analysis cellular representation is created by applying the virtual topology operations corresponding to the decomposition of the original topology based on [2] and [3]. Therefore, adjacency information for the decomposed volumes is automatically retained by the non-manifold nature of the analysis topology.

In [2] and [3], cutting faces are used to partition the geometry in the CAD environment, creating a collection of manifold bodies. Certain interface information is not captured during the manifold decomposition, leaving it difficult to automate the mesh generation process. For example, dissimilar pairs of faces can appear between bodies after successive splits. In Fig. 3(a), the equivalence between the manifold and non-manifold interfaces is obvious for simple splits (Fig. 3(b)), but if the bodies are further decomposed (Fig. 3(c)), the manifold entities at the interface become incompatible. In such cases, virtual topology operations ensure that missing entities (red in Fig. 3(c)) are captured in the non-manifold representation [5], which is robustly coupled with the manifold representation.

A virtual topology relation in the database records the history of the decomposition by linking the analysis topology to the original manifold design topology, hence linking the decomposed model with the design model. Different identifiers are required to robustly map entities across packages, especially since the model can be converted to polygon faces and edges in CAE packages.

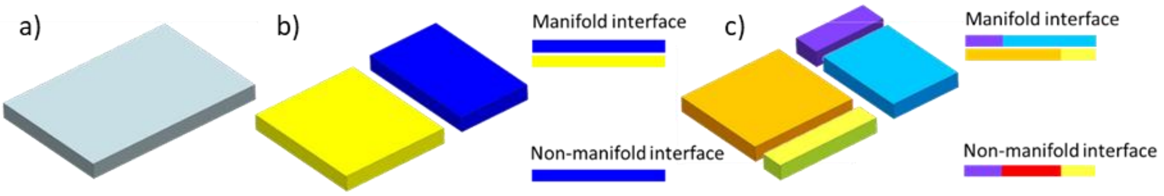


Fig. 3: Missing non-manifold entities.

The non-manifold cellular representation is further enriched by assigning attributes to appropriate analysis entities, e.g. recording whether a cell can be meshed by a sweeping operation, and if so what the source and target faces for the sweep are (Tab. 1). Specific entities in the analysis topology have a mesh type assigned. This includes the appropriate interfaces where mesh compatibility is defined by the mesh type assigned to the parent cells of the interface.

| *Analysis attribute* | *Mesh type* | *Method* | *Analysis variable* |
|---|---|---|---|
| Thin-sheet (TS) | Hex | Swept | Aspect ratio/number in thickness |
| Long-slender (LS) | Hex | Swept | Inherited from TS |
| Residual (R) | Tet | Automatic Tet | Inherited from TS |
| Source faces | Quad | Mapped/paved | High aspect ratio |
| Residual interfaces | Pyramid | Tet combination | Small aspect ratio |

Tab. 1: Analysis attributes extracted during the decomposition.

*Meshing Recipe*

In order to ensure that a good quality mesh is produced, the mesh metrics have to account for the geometry configuration and properties, as well as the connectivity between different cells. By using a set of simple topological queries such as identifying whether the connecting edge/face is a source or wall entity (in the sweep direction or not), specific meshing configurations can be identified (Fig. 4). For example, two thin-sheets connected by an edge which is in the sweep direction and bound a source face (wall-source edge) identify an area where a denser mesh is likely to be required. Then, mesh controls can be automatically applied.

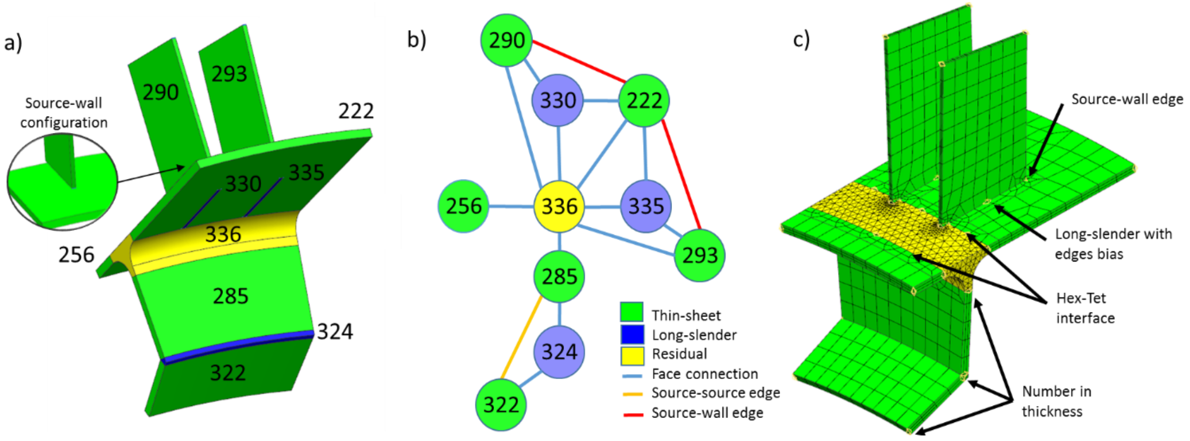


Fig. 4: (a) decomposed model, (b) connectivity graph, and (c) configurations identified.

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In order to reduce the number of degrees of freedom in the overall model, anisotropic elements are applied to long-slender and thin-sheet regions. The analysis variables for the thin-sheet regions are user-defined target aspect ratio and number of elements through the thickness, as shown in Tab. 1. All other variables are derived automatically using adjacency information, hence all the elements sizes are defined. The connectivity graph also enables interfaces between tet regions and hex regions to be processed, where a size transition is required between the isotropic and anisotropic elements to avoid poor quality elements. Fig. 5. Shows an example of different aspect ratios at the hex-tet transition.

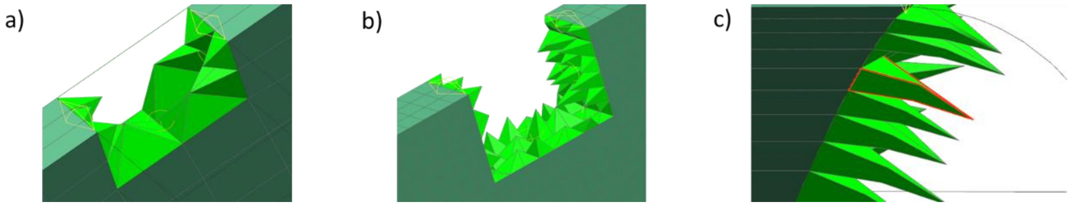


Fig. 5: Pyramid transition elements: (a) aspect ratio =5, (b) aspect ratio =1, (c) failed element.

The interval assignment problem can be formulated into a linear program and solved [1] in order to define suitable and compatible element division numbers on edges. This is achieved in four steps. First, the problem is initialized by finding the number of variables and which edge intervals should be optimised. Then each edge has a variable assigned, and a geometric query gives the initial number of divisions or goal for edges which have a target size assigned. In the following step, the constraints which control how the sizing propagates throughout the model are extracted from the database. Each wall face will need to be mapped to comply with the sweeping constraint, and queries can identify mappable source faces which will improve the mesh structure. On the other hand, transition zones are automatically defined to avoid denser mesh propagating from small features to bigger ones. This is achieved by replacing the mapping method with a paving method where the difference of goals is large between constrained edges. The aim of the optimization is to identify a set of intervals as close as possible to the targeted number while ensuring everything is compatible. The objective function is defined by Eqn. (1) and (2) as follow:

- Minimize difference delta of the variable $x_i$ to a pre-set goal $G_i$

$$|x_i - G_i| = \Delta_i \tag{1}$$

- Linearize the constraints

$$|x_i - G_i| = D_i + d_i \tag{2}$$

  - With $D_i \geq x_i - G_i$ and $d_i \geq -x_i + G_i$
  - Need to minimise $D_i \geq 0$ and $d_i \geq 0$ (in the objective vector)
- Apply weights $w_i$ and $W_i$ to make denser mesh prevalent
- Objective function : Minimise $\sum W_i D_i + w_i d_i$

Further transition can be defined a posteriori where the difference between the target and the solution is too large. By creating an offset, the size variation elements can be contained and the rest of the body can receive a structured hex-mesh.

*Meshing*

Once the meshing recipe has been defined, the model can be meshed in the CAE environment. Mesh mating conditions are extracted from the database and applied. Long slender regions are meshed first since they are the most constrained, Fig. 6(b) and 6(c), followed by thin-sheets, Fig. 6(d) and 6(e). A quad mesh is applied on a source face, and swept to generate hex elements. Then, residual regions are tet-meshed, Fig. 6(f), and a layer of pyramid elements is inserted to ensure a fully conformal mesh at interfaces with hex-regions.

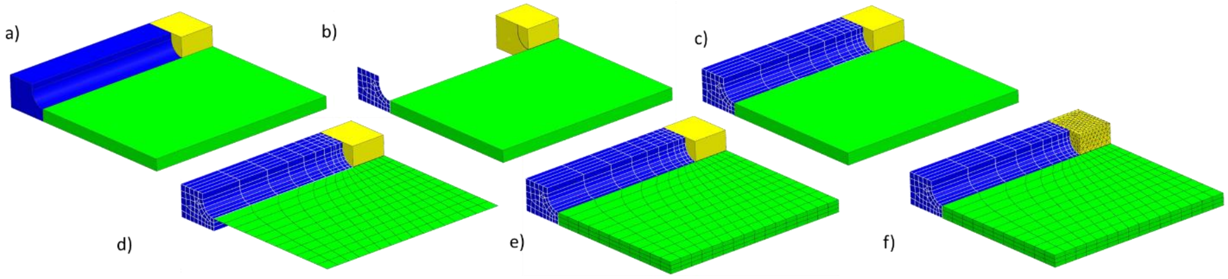


Fig. 6: Meshing sequence for a simple component.

The component in Fig. 7(a) can be decomposed in within 35 seconds into 61 bodies Fig. 7(b), and a 75% hex-dominant mesh Fig. 7(c) is obtained in 67 seconds, generating 57,000 elements.

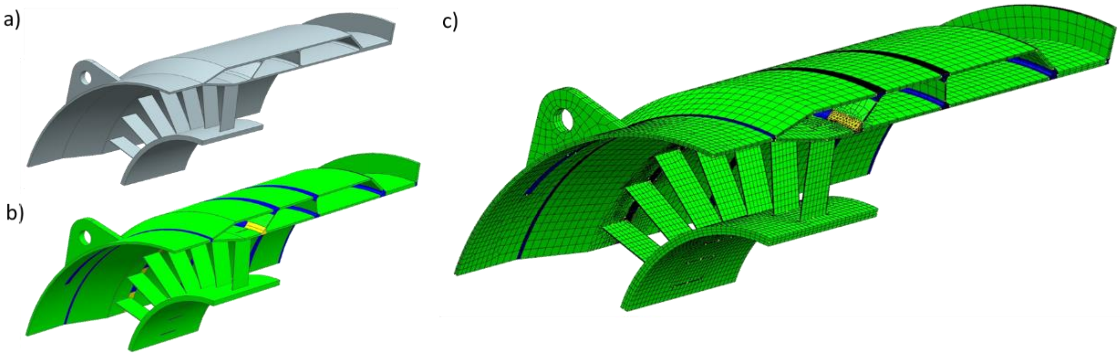


Fig. 7: Automatic decomposition and meshing of a compressor casing mock-up.

Conclusions:

The implementation of an independent non-manifold data structure is used to manage various analysis representations. This allows a manifold decomposition to be been enriched using virtual topology operations to record the subdivision history and also maintain robust links with the design component. The resulting non-manifold cellular model and its interface information and analysis attributes have then been used to automatically define meshing recipes required to generate a hex-dominant mesh

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