Title:
Efficient Symmetry-Based Decomposition and Meshing For Quasi-Axisymmetric Assemblies

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Introduction:
Significant advances in computational hardware and finite-element analysis (FEA) tools have seen a dramatic increase in the models and physics to be analyzed. However, resources are still stretched to their limits when dealing with large models (i.e. whole-engine aero model) and more advanced analyses (i.e. non-linear fan blade-off analyses). To this end, symmetry properties of components, which include geometry, loading, boundary conditions and material properties, are often exploited to reduce simulation run-time by reducing the numbers of degrees of freedom (DOF) in the idealized analysis model. Whilst symmetry idealization is a well-established pre-processing tool for analysis model generation it has not been exploited to simplify mesh generation. Mesh generation can often be a major bottleneck in analysis processes, especially for the creation of hexahedral (hex) meshes. In the absence of automatic hex meshing algorithms the ability to identify symmetry properties enables the partitioning of a complex model into simpler, repeatable sub-domains. This reduces the manual meshing burden required to generate hex meshes as only a portion of the model needs to be meshed and the full mesh can be generated by applying the symmetry operators used to partition the model. Another level of meshing complexity is introduced when dealing with assembly models where there is a requirement to have conformal meshes between adjacent components. Therefore, assembly configurations require any symmetry-based component decompositions to be compatible between adjacent components.

In this paper the aim is to use symmetry properties of components with assembly interface information to decompose quasi-axisymmetric assembly models into symmetric sub-regions and asymmetric residuals. The symmetry-based decomposition an equivalent meshable representation which can be utilized for hex mesh generation using multi-sweeping.

Related work:
Symmetry detection has been widely studied in the computer graphics community and can be classified in terms of global or local (partial) symmetry and exact or approximate symmetry [7]. Numerous methods have focused on finding symmetries in mesh models [5] and B-Rep CAD models [3]. Symmetry detection has been developed for assembly planning [7], detecting design intent [4] and for restructuring feature trees [3]. Automatic symmetry detection has often been focused on single components within assemblies without consideration of assembly configurations [3]. Vilmart [9] describes the use of a knowledge-based approach combined with the symmetry analysis from Li [3] and geometric interface information to extract repetitive patterns of sets of components within assembly configurations. In this work the aim is to use geometric interface information in assembly to help propagate symmetry properties between components to facilitate conformal hex meshing of assemblies.

Limited research has focused on the use of symmetry properties for mesh generation. Suresh [6] detects global symmetry in 2D cyclic sketches and linearly 3D swept solids. Tautges [9] uses a lattice structure to exploit symmetry and create meshes for nuclear reactor geometry assemblies. These approaches are limited to 2.5D geometries with simple sweep directions. This highlights the need for more complex symmetry decompositions to extract partial symmetry properties within 3D geometries.

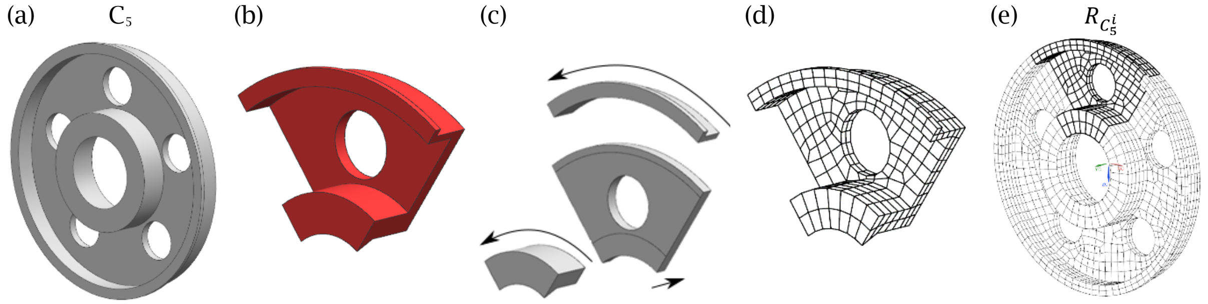


Fig. 1: Global symmetry-based decomposition: (a) B-Rep CAD model exhibiting C_5 cyclic symmetry, (b) cyclic sector, (c) sector decomposed into sweepable bodies for multi-sweeping with arrows representing sweep direction for each sub-region, (d) sector mesh, (e) fully patterned mesh.

<u>Symmetry-based decomposition for hex meshing:</u>

Symmetrical properties of geometries include cyclic (or rotational), reflective and translational symmetries, or combinations thereof. Quasi-axisymmetric components and assemblies are defined as having a major axis about which most of the geometry is symmetric. Therefore, in this paper the focus is on the identification and processing of the axisymmetric and cyclic symmetric portions of the geometry that are prevalent in quasi-axisymmetric components. N-fold rotational symmetry around a central point in 2D or an axis line in 3D is referred to as cyclic symmetry, denoted by C_n which describes the set of rotation transformations $R_{C_n^i}$ through an angle $\alpha=2\pi i/n$ where $n\geq2$ and $i \in [1, n-1]$. Axisymmetric properties are a special case of cyclic symmetry where n = ∞ and is denoted by C_∞.

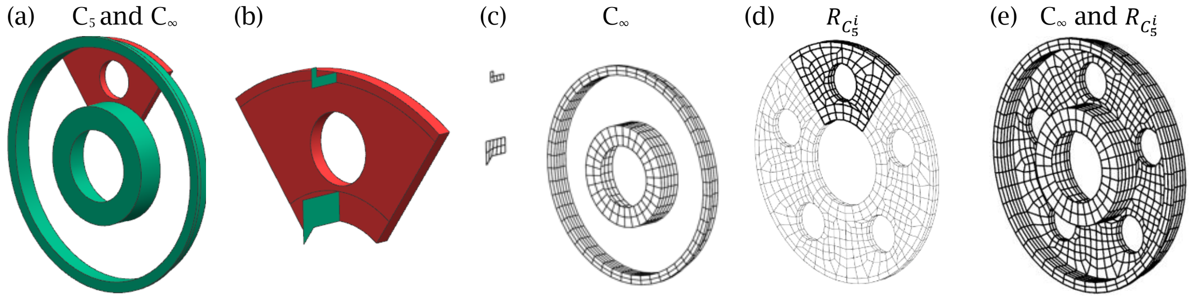


Fig. 2: Local symmetry-based decomposition using Fig. 1 (a) as input model: (a) Local isolation of symmetry regions, axisymmetric (C_∞) in green, cyclic (C_5) in red, (b) equivalent meshable representation, (c) axisymmetric mesh generation, (d) cyclic mesh generation, (e) full component mesh.

Global symmetry is restricted to cyclic and reflective symmetry types, whereas partial symmetries can exhibit all symmetry types that are represented by decomposition into sub-regions to isolate the partial symmetries. Fig. 1 illustrates an example exhibiting global cyclic symmetry, C_5. Once the cyclic sector has been extracted, further manual decomposition enables a multi-sweeping type approach to be used to define the sector mesh. Since cyclic, reflection and translation symmetry transformations are Euclidean maps as original lengths and angles remain invariant they can be applied to the meshes generated on components exhibiting these symmetry characteristics. This enables the full component mesh in Fig. 1 (e) to be generated using the $R_{C_5^i}$ transformations on the cyclic sector mesh in Fig. 1 (d). Whilst global symmetry can be exploited for simplifying FEA models, it is often desirable to extract local or partial symmetry properties for hex mesh generation, especially for complex CAD models where global symmetry often doesn't exist. Fig. 2 shows decomposition and meshing of the component in Fig. 1 using the process described in [1] to extract the local symmetry properties and in-effect generating similar decompositions as required for the multi-sweep in Fig. 1 (c). This decomposition isolates axisymmetric and cyclic symmetric regions in the component automatically, Fig. 2 (a), and generates an equivalent meshable representation suitable for hex meshing, Fig. 2 (b), where axisymmetric regions are represented by their 2D axisymmetric profile. This equivalent meshable representation consists of the smallest number of meshable primitives, alongside their associated transformation matrices, required to generate the full component mesh, Fig. 2 (e).

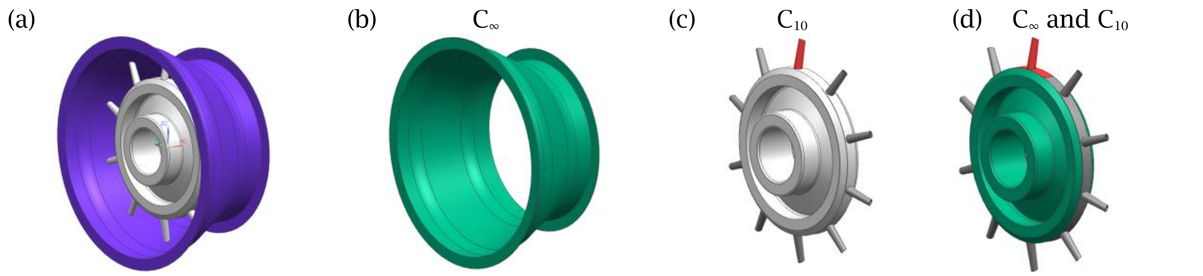


Fig. 3: Symmetry-based decomposition: (a) CAD assembly, (b) outer casing identified as axisymmetric (green), (c) identification of cyclic faces and groups (red faces are the master group and grey the repeated), (d) decomposition of hub into axisymmetric (green), cyclic (red is cyclic and grey is repeated).

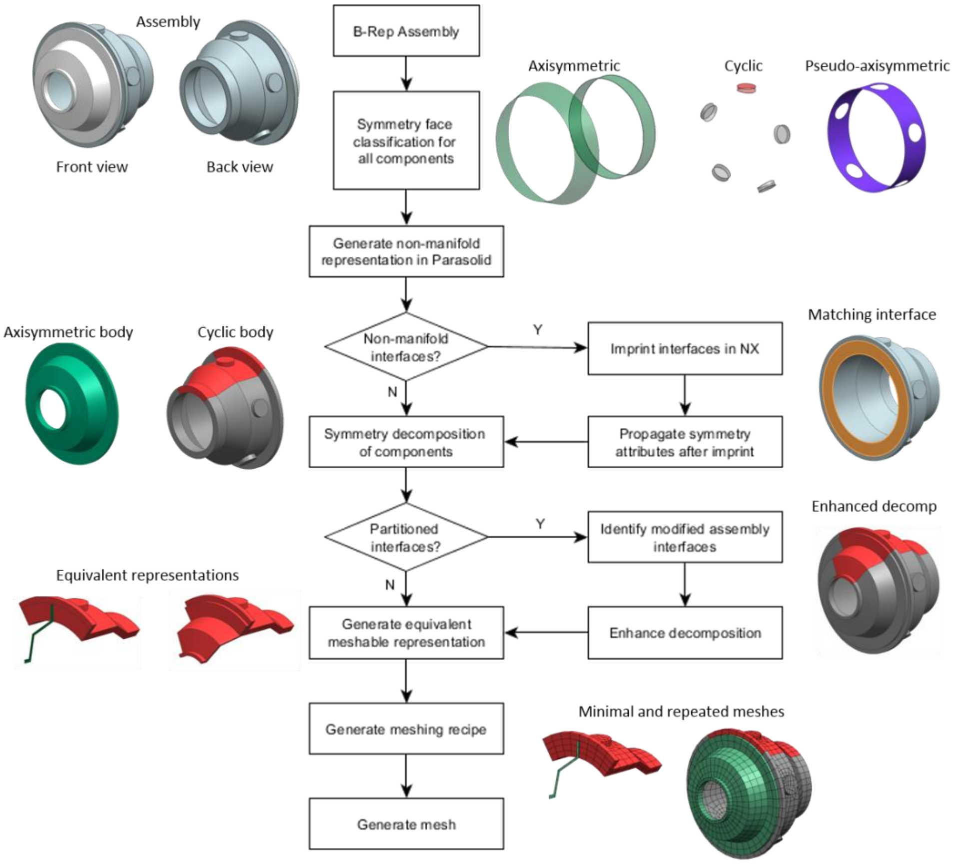
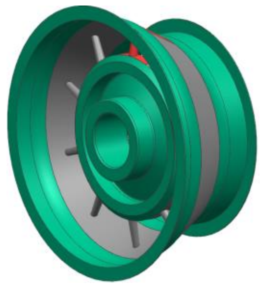
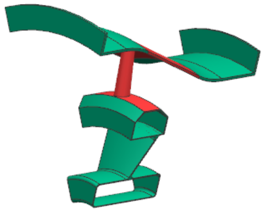
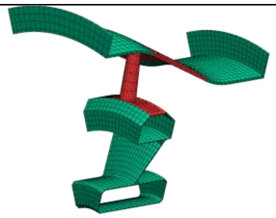
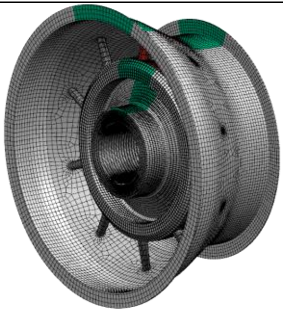
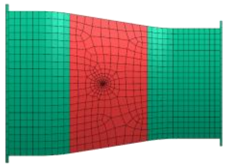
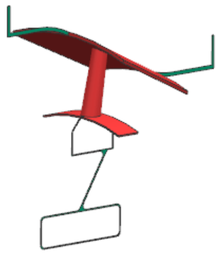
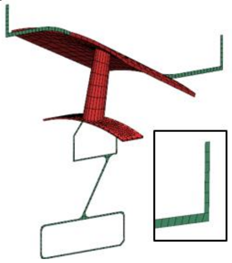
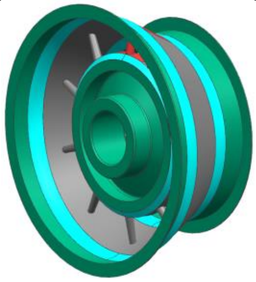
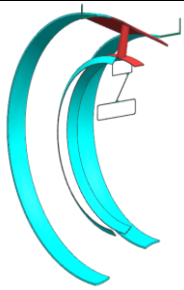
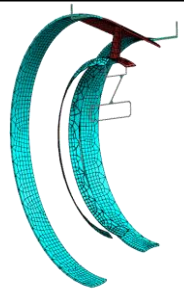
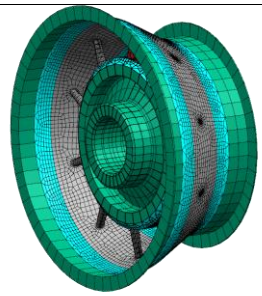


Fig. 4: Workflow of assembly decomposition approach.

Symmetry detection and decomposition

Previous work [1] by the same authors describes a symmetry detection and decomposition approach for B-Rep CAD models, depicted in Fig. 3. The main hypothesis is to consider the axis of rotation z-axis as known to classify faces as axisymmetric, cyclic symmetric, pseudo-axisymmetric and non-axisymmetric. Pseudo-axisymmetric faces have axisymmetric surface definitions but non-axisymmetric boundaries, i.e. an axisymmetric face with inner loops. Once faces have been classified the symmetric portions of the boundary are processed. Fig. 3 (b) shows the outer casing of the assembly is identified as axisymmetric since it is bounded by all axisymmetric faces. Cyclic symmetry detection outputs repeated sets of cyclic faces where each face in the set is congruent with all other repeated entities. These sets of faces are then grouped into cyclic group patterns, denoted as G_n, with *n-fold* symmetry and *n* groups consisting of a combination of cyclic faces defined within that pattern. As for face sets each cyclic group is congruent to all others in the group set. After isolating axisymmetric portions of the model boundary, Fig. 3 (d) green subsets, cyclic portions of the boundary are isolated, Fig. 3 (d) red. Prior to decomposition all faces in the cyclic boundary portion are cyclic, axisymmetric or pseudo-axisymmetric. After decomposition all faces are cyclic and their repeated definition. Whilst a valid hex mesh is generated connection elements are required to couple the incompatible meshes of the inner and outer structures. In order to achieve a fully compatible and contiguous hex mesh compatible interfaces between components need to be identified. The workflow in Fig. 4 shows the process of defining the compatible interfaces and propagating them through the decomposition, with updated decomposition of Fig. 3 shown in Tab. 1.

Decomposition	**Equivalent meshable representation**	**Equivalent mesh**	**Full conformal assembly mesh**
			 
			
			

Tab. 1: Different decompositions and equivalent mesh representations based on simulation intent.

Equivalent meshable decomposition

Simulation Intent refers to the high-level analysis decisions required to generate fit-for-purpose analysis models. Tab. 1 illustrates how different simulation intent definitions are used to create different

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decompositions required to generate fit-for-purpose meshes. The first decomposition yields a fine mesh that may be required for a more detailed stress analysis. Two different equivalent meshable representations can be generated to define the same fine mesh. The only difference is how the axisymmetric regions are treated. Since a fine mesh is required the small element size from the cyclic regions are propagated through the axisymmetric region. To achieve this the axisymmetric cells in the decomposition can be converted to C_{10} cyclic cells, which makes them sweepable. Mesh density is propagated across the cyclic-axisymmetric interface and the resulting swept mesh is repeated using the cyclic transformation $R_{C_{10}^{i}}$. The other option is to idealize the axisymmetric regions to their 2D axisymmetric profile, which are quad meshes and revolved to generate $C_{10} \times N$ hex elements around the circumference, where N is the number of nodes on the cyclic-axisymmetric interface. Cyclic periodic faces are constrained to have compatible meshes, this enabling fully contiguous hex meshes to be generated. The second decomposition is defined to reduce the DOF in the hex mesh, i.e. for a whole engine fan-blade off analysis. To generate an efficient mesh it is desirable to transition between smaller mesh densities in the cyclic regions, where more detail exists, to larger mesh densities in adjacent axisymmetric regions. The axisymmetric regions are decomposed further to create transition regions, Tab. 1 blue regions, where the mesh is swept through the thickness of the region as opposed to along the circumference for the axisymmetric region. Transition regions exhibit C_∞ reflective planes so only half is represented in the equivalent representation, with an associated reflection transformation.

Conclusions:

This paper introduces a symmetry-based decomposition approach to isolate axisymmetric and cyclic portions and propagate these properties between assembly components. Different equivalent meshable representations and therefore different fit-for-purpose hex meshes are automatically defined depending on the simulation intent specified by the analyst. Utilizing the equivalent meshable representations with the appropriate transformations significantly reduces the burden required to mesh the overall assembly.

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