Title:
Recognition and Decomposition of Rib Features in Thin-Shell Plastic Parts for Finite Element Analysis

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Introduction:

Mold flow analysis is commonly used in injection molding to assist in designing injection molds as well as setting the process parameters. In mold flow analysis, it is necessary to convert the computer-aided design (CAD) model into solid meshes so that the solver can perform computations. Traditionally, tetrahedral meshes are used because they are easy to generate automatically, but this type of mesh is of the lowest quality compared with other types (e.g., pyramidal, prismatic, or hexahedral). Hexahedral meshes are highly preferable to tetrahedral meshes for their greater accuracy, convergence, and application specificity. However, hexahedral meshes are inherently trickier to generate because they require the careful decomposition of the CAD model. The generation of entirely hexahedral meshes on a CAD model may be difficult, but a hybrid combination of hexahedral and prismatic meshes is possible and can solve the problems of tetrahedral meshes.

Typical methods for generating regular types of meshes such as hexahedral and prismatic meshes, are mapping and submapping, meshing primitives, and sweeping. These require the decomposition of some recognized patterns from a CAD model and the conversion of each of them into meshes using one of the aforementioned meshing algorithms [5]. Feature recognition has been studied for decades and several feature recognition methods are available on commercial CAD systems. However, these methods are primarily for applications in CAD, computer-aided manufacturing (CAM), and computer-aided process planning (CAPP); they may not be appropriate for application in finite element analysis (FEA) because the data extracted is not suitable for meshing. Combining multiple meshing algorithms and mesh types to deal with practical CAD models is necessary.

Ribs are a common feature in CAD design, appearing frequently in many products. In particular, they are often designed on thin-shell plastic parts to enhance the strength of the structure. Ribs are generally designed as a series of interconnected structures distributed across the inner surface of a thin-shell part to provide the required strength. The shape design and distribution of ribs can affect the quality of the injecting part. One defect often associated with ribs is that some regions on the outer surface of a thin-shell part may be sunken slightly because of shrinkage of the material near the regions on the inner surface where several ribs intersect. An accurate simulation of such a phenomenon is necessary to provide a deeper understanding of the physical mechanisms so that its occurrence can be avoided. As the rib structure on thin-shell parts can be highly complex, an improved meshing method is necessary to adjust the size, shape and mesh type in various regions of the shape.

The feature data extracted from various feature recognition methods are generally not sufficient for solid mesh generation because they are primarily used to describe feature shape. Several approaches are available in the literature to decompose, extract or simplify solid models and thereby obtain such data. Chong et al. [2] focused on idealizing finite element models and proposed some operations to allow user to automatically reduce the dimensionality of geometric models by using a decomposition and reduction method. However, they essentially approximated a three-dimensional problem with two-dimensional meshes, which might not be sufficient accurate. Boussuge et al. [1] proposed an idealization approach based on generative shape processes to decompose solids. They provided a graph containing all nontrivial construction trees using generative processes, which is more useful for evaluating variations of idealization. However, they also deal with two-dimensional meshes only. Makem et al. [6] generated shape metrics by using local sizing measures to identify long, slender regions within a thick body, and then proposed a procedure to partition the thick region into a non-manifold assembly of long, slender, and complex sub-regions. However, the models that can be handled are limited. Juttler et al. [3] presented a technique for segmenting a solid model with an edge graph of only convex edges into a collection of topological hexahedra. Although the meshes used are hexahedral meshes, the distribution of the meshes are irregular and cannot be controlled. So, the complexity of the models that can be handled is limited. Also, no fillet is allowed on the models.

Regarding rib definition and recognition, Owodunni et al. [7] defined a rib feature as an additive, prismatic machining feature. They employed properties such as the closure of a feature shape along the x, y and z axes for the classification of 2.5D types. Li et al. [4] defined ribs as a set of constrained and adjacent faces of a part, which are associated with a set of specific rib machining operations. They formulated a set of rules, based on machining knowledge and combined with a holistic attributed adjacency graph, in a feature recognition algorithm. Zhu et al. [8] proposed a semantic mid-surface abstraction method for the thin-walled models based on rib-feature recognition. The model decomposition was conducted based on the identified rib features and the hierarchical semantic information. All discrete features and model regions were finally stitched to yield the final mid-surface model. Based on the aforementioned literature survey, it is clear that current feature recognition and decomposition methods are still not satisfactory for industrial applications because of the complexity and variety of the geometric and topological designs of real CAD models.

Main Idea:

As Fig. 1(a) depicts, a single rib stands alone on the CAD model. It can be decomposed individually as a region and easily converted into hexahedral meshes. A rib structure, however, is formed by a series of ribs that connect together. Its geometry is complex, and it must be decomposed into separate regions so that each of them can be meshed individually. Rib structures are divided into regions as either “rib segments” or “transition regions.” A rib segment has a pair of matching faces that are symmetric or almost symmetric. A transition region is the junction of several rib segments. Each transition region must be separated from the rib structure and meshed individually.

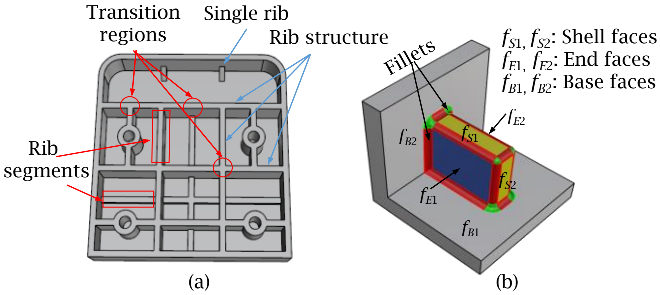

Fig. 1: Basic structure of ribs, (a) two basic patterns: rib segment and transition region, (b) three types of adjacent faces on a rib segment: shell faces, end faces and base face.

Fig. 1(b) depicts the basic attributes of a rib segment, including two end faces, shell faces, and base faces. The two end faces represent the matching faces of the rib segment, which are parallel or almost parallel to each other. The number of shell faces and base faces can vary. Also, a fillet may occur at the transition of two adjacent faces. Fig. 2 classifies various types of single ribs and rib structures. In Fig. 2(a), the “single shell face” case is the simplest, and the “multiple shell faces” case is the most complex because “virtual faces” have occurred on the rib. A virtual face is one that covers multiple regions in a CAD model. In Fig. 2(b), the shell faces at the junctions are of the same height, whereas in Fig. 2(c) the

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shell faces at the junctions vary in height. The intersection of the horizontal and vertical ribs can be an X-connection, T-connection with overlapping or without overlapping.

The present study proposes an approach for generating high-quality solid meshes for FEA applications that is based on feature recognition. Although feature recognition has long been studied, its application in FEA has not been investigated extensively. In particular, this study focused on the development of a rib recognition algorithm, the output of rib data for meshing, and the development of a process for automatic rib meshing. Because ribs are usually formed as a series of structure residing on a part, the proposed algorithm involves a decomposition strategy to separate a rib structure into a set of regions, and the evaluation of the data required for all regions.

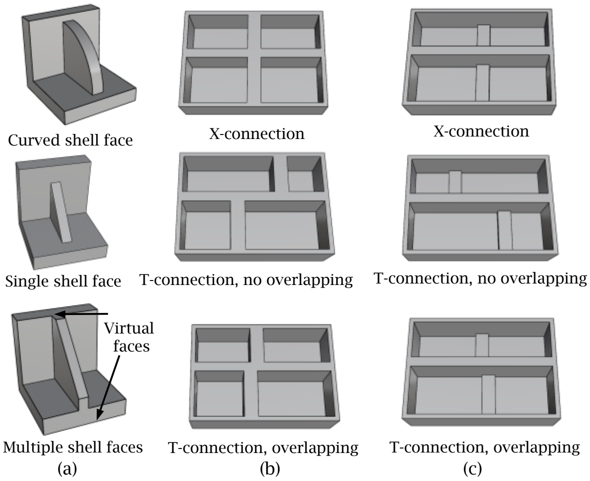


Fig. 2: Different situations of ribs, (a) three types of single ribs, (b) three types of junctions with equal height, (c) three types of junctions with different height.

Fig. 3 is a flowchart of the proposed feature recognition and decomposition method for ribs, where the input is the B-rep model of an object and the output is the data of all rib regions and the corresponding slicing faces for each of them. The user must assign the maximum thickness allowed (t_{max}) for ribs. The proposed method is divided into three parts: preliminary functions, rib recognition, and rib decomposition. The objective of preliminary functions is to prepare two databases for rib recognition and decomposition: an edge AAG database, which records the topological and geometric information of all edges, and a face AAG database, which records the same information for all faces. The objective of rib recognition is to find all rib segments. The set of shell faces and base faces adjacent to both end faces are also computed. The objective of rib decomposition is to compute all regions so that they can be decomposed one by one. The faces that cross distinct rib segments are divided and regenerated so that each rib segment has its own faces, and the data for all transition regions are also computed. Finally, a set of slicing faces for each region is evaluated so that all regions can be separated from the CAD model.

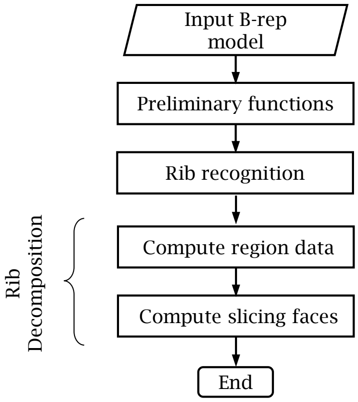


Fig. 3: Flowchart of the proposed rib recognition and decomposition algorithm.

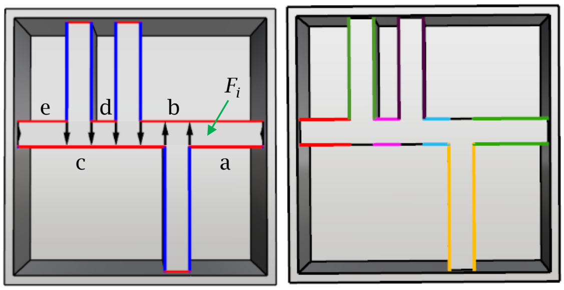
<u>Rib recognition:</u>
In rib recognition, all faces on the CAD model are tested in sequence to search for rib segments. The rib recognition algorithm includes three major procedures: searching for pairs of parallel edges, searching for end faces, and searching for shell faces. If all three procedures succeed, a set of rib segments can be recognized and the attributes for each of the rib segments computed. This process is repeated continuously until all faces on the CAD model have been tested. For all three procedures discussed below, F_i represents the face tested.

Step 1: Search for pairs of parallel edges
The end faces of a rib segment are a pair of matching faces that are parallel or almost parallel to each other. The objective of this step is to find multiple pairs of parallel edges for F_i. For example, the face F_i in Fig. 4(a) is a virtual face that lies across several ribs. There are 17 edges in F_i, divided into two groups: horizontal edges and vertical edges. On each group of parallel edges, an algorithm is implemented to divide them into pairs. For each end point of the edges, the matching edge with the minimum distance

to this point is computed. Once all matching edges are obtained, effective pairs of matching edges can be evaluated. If the two end points of an edge map onto the same edge, this pair of edges is an effective pair. For example, a^s -> b, a^e-> b where the superscripts s and e denote the starting and end points of an edge, respectively, and the symbol -> denotes the mapping. Fig. 4(b) depicts the result of searching for pairs of parallel edges in the example of Fig. 4(a).

Step 2: Search for end faces

A rule-based search algorithm is proposed to determine the end faces for each pair of parallel edges associated with F_i. Candidate faces neighboring each parallel edge are obtained by using the edge AAG database. If either of them is an EBF, the face AAG database is employed to pass over it and obtain the correct candidate face. Once a pair of candidate faces is obtained, the following six rules are employed to check if they satisfy the conditions of end faces. F_c represents a candidate face under consideration: (1) both candidate faces should be planes. A standard meshing algorithm can be employed to convert such a rib segment into hexahedral meshes; (2) the number of concave edges on F_c must be larger than 1; (3) if inner loops exist on F_c, all edges on the inner loops should be convex edges; (4) two base faces neighboring two distinct concave edges should be adjacent to each other; (5) two candidate faces F_c are not adjacent to each other; and (6) the effective angle of two candidate faces F_c is $180 \pm \varepsilon^o$. Here ε is typically set to 8^o. The tests should be performed for both candidate faces F_c. If all six rules are satisfied, then these are regarded as the end faces of F_i. Otherwise, no end faces are found for F_i.



(a) (b)

Fig. 4: Search pairs of parallel edges, (a) evaluation of horizontal pairs of edge segments, (b) final pairs of edge segments, where seven pairs of parallel edges are found.

Step 3: Search for shell faces

As many shell faces may exist on a rib segment, as shown in Fig. 1(b), the end faces must first be found from F_i, and then all shell faces must be obtained from the end faces. The edge between an end face and a base face is concave, whereas the edge between an end face and a shell face is convex. This property is employed to distinguish the type of face that neighbors an end face. When a fillet exists between any of these two faces, the face AAG database can be employed to pass over the fillet and obtain the correct neighboring face. The procedure to search for shell faces from a pair of end faces (f_{E1} and f_{E2} in Fig. 1(b)) is performed by checking all edges of both end faces. Once this process is complete, all shell faces related to the pair of end faces f_{E1}-f_{E2} can be obtained.

Rib Decomposition:

The data recorded in rib recognition represent the edges and faces involved in each rib segment, but they are still insufficient to describe an individual region because some of the entities exist across multiple regions. Furthermore, the data to describe transition regions have still not been considered. Therefore, the purpose of rib decomposition is to compute the data required for decomposing each region, both rib segments and transition regions. The region data are primarily composed of two parts: boundary edges and slicing faces. The former describes the connecting edges of a region and the rest of the model, and the latter describes the faces required to decompose a region.

Step 1: Divide all shell faces into loops

A loop is formed by four edges that connect to each other in sequence. The loops on a shell face come from both types of region, rib segments and transition regions. The pairs of edges on a shell face are employed to evaluate the loops, with respect to rib segments first. The edges that link each pair of edges are also generated. The loops from transition regions are then computed using the link edges, as shown in Fig. 5(a).

Step 2: Subdivide loops and compute boundary edges for all rib segments
A loop must further be subdivided at the junction of different heights so that the shape at the junction can be recognized and decomposed as an individual region. For example, the yellow loop shown in Fig. 5(a) must be subdivided because a T-junction of different heights occurs. The pair edges of these rib segments on the shell and end faces are employed for detecting and subdividing such a loop. The example shown in Fig. 5(b) depicts two sets of boundary edges obtained for two rib segments R_r. The regions R_r for rib segments are the output of this step. The data for each region includes boundary edges and slicing faces. The boundary edges for regions owing to rib segments are evaluated. It is only necessary to generate link edges to connect each pair of edges and form the required loops for slicing faces.

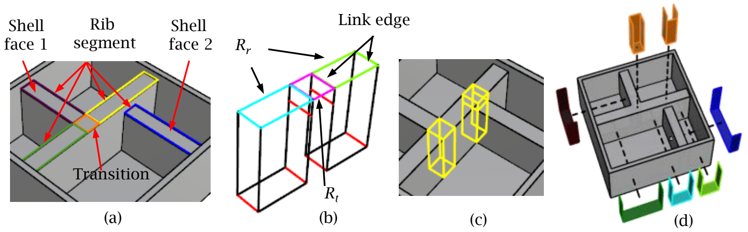


Fig. 5: Immediate results of rib decomposition for the first CAD model, (a) the CAD model and five loops obtained by dividing both shell faces, (b) subdivide a loop with two intersected ribs of different height to yield three loops, (c) boundary edges for all transition regions sharing the same shell face, (d) seven set of slicing faces generated, corresponding to seven regions, respectively.

Step 3: Compute boundary edges for all transition regions
The boundary edges corresponding to the regions R_t are computed. Each loop on a transition region is also composed of four edges. If an edge is adjacent to a rib segment, the corresponding boundary edges can be obtained by using those from the neighboring rib segment. All boundary edges can then be arranged in sequence to form the loops required for slicing faces. The example shown in Fig. 5(c) depicts two sets of boundary edges obtained for two transitions.

Step 4: Compute slicing faces for all regions
Once all boundary edges are obtained, every four boundary edges are arranged in sequence to form a loop. Given that all slicing faces are planes, each loop of four boundary edges can be used to generate a planar face. This process is repeated for all loops to yield all slicing faces. The slicing faces corresponding to each region can be grouped and employed later for the decomposition of the region. Fig. 5(d) depicts the slicing faces for all regions extracted.

<u>Results and discussion:</u>
We tested feasibility with a program based on the proposed algorithms, written in C++ and based on the Rhino CAD platform and the openNURBS function. Fig. 6 illustrates examples of the rib recognition results obtained; the ribs are shown in blue. Shape complexity ranged from simple individual ribs to several interconnected rib structures. Ribs recognized successfully in this study include rib structures located on several surfaces or irregular faces and a rib structure with a mixture of segments of equal and different heights.

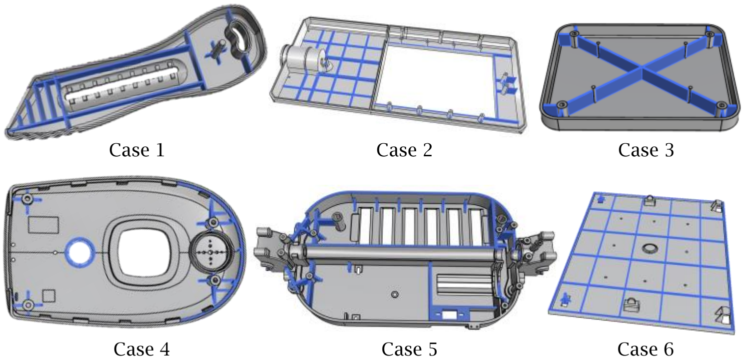


Fig. 6: Results of the proposed rib recognition algorithm for six CAD models.

Fig. 7 depicts the decomposition results for one CAD model, in which both T- and X- connections exist, as well as rib segments of both equal and different heights. Four tubes also appear on the model and intersect with the rib segments. The main purpose of this example is to demonstrate the generation of high-quality solid meshes for ribs. All boundary edges and slicing faces can be generated automatically. All of the rib segments and transition regions are meshed using hexahedral and prismatic meshes, whereas other parts of the model are meshed using BLMs. All quality indices, such as the mesh number, orthogonality, aspect ratio, and skewness, have improved considerably for the ribs owing to the use of all hexahedral and prismatic meshes throughout. However, the indices are not improved for the other parts of the CAD model because the current algorithms are effective for ribs only. It would be necessary to extend the proposed method to handle a greater diversity of features to improve the mesh quality of the entire model.

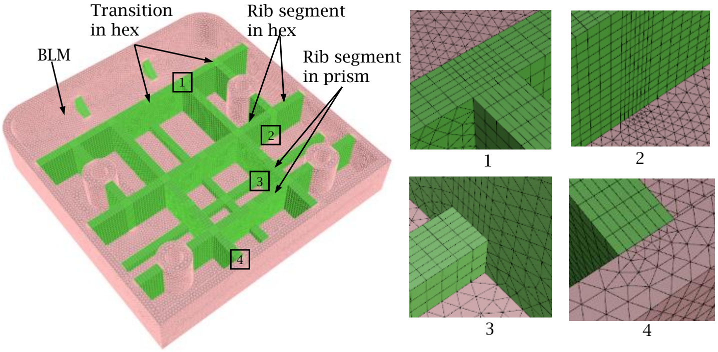


Fig. 7: Results of manual mesh generation in accordance with all regions generated in this study, where regular meshes are used for rib regions and BLM meshes are used for the other parts of the model.

Conclusion:

This study focused on the development of rib recognition and decomposition algorithms for thin-walled plastic parts, and verified the feasibility of the proposed algorithms using several CAD models. A procedure for generating hexahedral and prismatic meshes for ribs was also presented. Our approach is based on feature recognition and decomposition for generating high-quality solid meshes for FEA applications. An algorithm for the recognition of a rib structure was proposed that can not only be used for ribs but also expanded to other features. This method can reduce the necessity of manual operation, hence decreasing the overall operational time for meshing. Furthermore, the meshing results indicate that the quality indices of the meshes generated using the proposed method improved considerably in comparison with the results of previous methods. The proposed meshing algorithm is feasible only for recognized ribs, however. Future studies should develop additional feature recognition and decomposition algorithms for converting more CAD model features into hexahedral meshes.

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